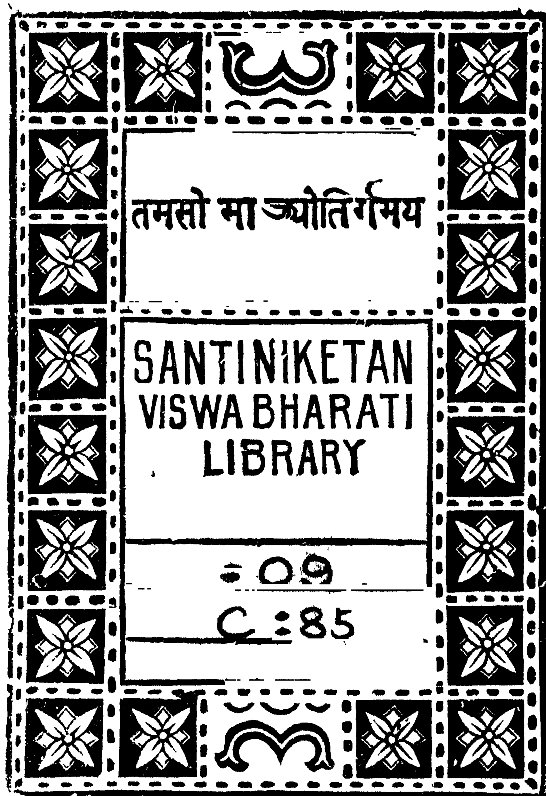


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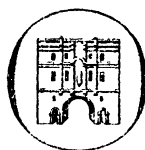
DISCOVERIES AND INVENTIONS OF THE TWENTIETH CENTURY

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by

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EXTRACT FROM THE PREFACE TO THE FIRST EDITION

HAVING regard to all the circumstances, it was decided to deal with the characteristic features of development in certain selected fields of enterprise during the last twenty-five years. Thus the first five chapters discuss the revival of water-power, economy in the use of fuel, modern steam engines, gas, oil, and petrol engines, and the generation and distribution of electricity. These are followed by chapters on electric lighting and heating, new processes in the manufacture and treatment of steel, some typical modern devices in the engineering workshop and the factory, and the extraordinary number of manufacturing processes which have their birth in the electric furnaces. From the highest temperatures which man has, so far, been able to produce the book passes to a consideration of the artificial production of cold and its applications in the manufacture of ice, cold storage on land and sea, and the liquefaction of gases. This chapter is succeeded by one dealing with the interesting facts which have recently been discovered relating to the fertility of the soil and the yield and quality of wheat.

One of the most characteristic features of the twentieth century is the improvement in transport and communication, and Chapters XII to XVII contain some account of railways, electric traction, motor-cars, modern ships, aeroplanes and airships, and wireless telegraphy. The constitution and some of the weapons of a twentieth-century navy are described in Chapter XVIII; Chapter XIX deals with the photography of colour and of bodies in motion; and the book closes with a brief account of the recent marvellous discoveries relating to radium, electricity, and matter.

While the plan adopted is open to criticism, it has enabled a wide field to be covered, a fairly coherent picture to be drawn, and a limited amount of explanation to suffice. Numerous cross-references render immaterial the order in which the chapters are read. The terms 'discovery' and 'invention' have been interpreted liberally, so as to include

results of human enterprise which, though not embodying any new principle, yet rank as great achievements and are rendered possible by other results which fall legitimately under these headings. There appeared, moreover, to be a distant advantage in presenting any discovery or invention in close association with its practical relations. The aim, purpose, and value are thus emphasized, and the whole scheme contributes to sanity of outlook.

Considerations of space and the necessity of linking up the twentieth century with the past have led to the exclusion of much, even within the limited field covered, that should rightly have been included. But for this it seemed easier to offer an apology than to find a remedy. The book is written for those, young and old, who wish to have a non-technical account of the great scientific and material triumphs which man has achieved and is achieving in their own day; and it seemed desirable to give the first place to those theories, facts, and accomplishments which are now exercising the greatest influence upon human life. For science exists not so much to tickle the intelligences of the few as to brighten the lot of the many.

E. C.

September 1914

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I

THE REVIVAL OF WATER-POWER

PROBABLY one of the most important steps ever taken by primitive man in his unconscious efforts to escape from savagery was the discovery of the wheel. The fact that rolling produced less friction than sliding was but dimly recognized: the mechanical principle involved was perhaps but vaguely distinguished. There were no patent laws to protect the inventor, no legal formularies upon which he need enter, no manufacturers to whom licences might be issued and from whom royalties might be obtained. He was not absorbed by visions of untold luxury and ease. But he must soon have grasped the fact that here was a contrivance that would facilitate locomotion and increase his power over his surroundings. For this last, after all, represents the aim and destiny of mankind since the world began—an aim which is still paramount, though modern life is so complex that few know their bearings outside the small circle in which they live. This fortunate discoverer, together with he who first produced fire, were the forerunners of the engineers and manufacturers, the scientific discoverers and inventors of today. The wheel made it easy to move huge weights and to cover great distances, and when it was applied to spinning it transferred part of the burden of providing clothing from the animal to the vegetable kingdom. Rude skins gave place to finely woven fabrics, and the tiller of the soil vied with the hunter and the shepherd in covering man's nakedness.

At first the wheel was driven by manual toil or by the use of beasts, but when, after many centuries, wind and water were used, man saw opening up a wider vista which promised speed of production and more leisure to him who could harness the natural elements to his service. Was there joy when the first wheel turned in the wind, or a mad clapping of hands when one of these rough contrivances first creaked beneath the force of a mountain stream? We shall never know. In those days man was too much occupied with maintaining his existence. The art of speech was probably incapable of exact description; the arts of drawing

and writing too crude to permit of accurate record. And perhaps it is as well that some of these early events should be left to the imagination, so they may acquire a sanctity that fancy weaves about them and which exact knowledge might destroy.

It is hardly possible to realize that until the middle of the eighteenth century wind and water were the only means of obtaining power from the prodigal forces of Nature. Clothing, tools, weapons had been made, houses and ships had been built, and international trade had arisen, by hand labour and a few relatively unimportant waterfalls. The ruins along the narrow valleys east and west of the Pennine Chain indicate the birthplaces of the British textiles industries, where once fitful streams drove the looms that wove the fabrics for which Lancashire and Yorkshire have become famous.

England, however, is not rich in large waterfalls: puny streams could only aid in a small way the development of the factory system and were unable to compete with the steam-engine; so the industries vanished from the hillsides and reappeared amidst the sharp hiss of steam instead of the murmur of falling water. And if the suppression of water-power had been universal and permanent this chapter need not have been written. But it was neither. In other lands there are streams and waterfalls so large that those who have not seen them can have little conception of their real size and only a vague impression of the power they represent. These acquired a greater value when the progress of knowledge had shown how electricity could be produced and distributed, and during the last fifty years their value has been still further enhanced by the discovery of new electrical manufacturing processes.

Theoretically, any stream of water can be harnessed to produce power, the potential amount being given by the magnitude of the flow and the head through which the water falls. In general, only a small fraction of any large potential power can be harnessed by present technique and practice.

For instance, the theoretically usable water-power of North America has been estimated as equivalent to 960,780,000 h.p., more than half of which is in the U.S.A. American engineers estimate, however, that only about 124,620,000 h.p. is realizable by present practice. The aggregate installed capacity in the U.S.A. by 1948–9 was 22,244,000 h.p., and in Canada 10,870,000 h.p. Thus even in the U.S.A. only 3 per cent of the theoretically usable water resources are developed, and only 18 per cent of those developable by present practice. The latter figures for Canada are 20 per cent, and for Norway 16 per cent. The countries that are most advanced in hydroelectric development still have a long way to go.

According to figures given to the Fourth World Power Conference in 1950, the main theoretically usable water-powers of the world are:

	h.p.
Europe	268,000,000
Asia	3,092,720,000
Africa	1,747,700,000
North America	960,780,000
South America	1,487,400,000
Australasia	159,460,000
(United Kingdom	2,680,000)

The immense water-powers of Asia and Africa, at present almost entirely unharnessed, are particularly striking.

The theoretically usable water-power of the Yangtze has been estimated at 294,800,000 h.p., the Menam in the Malay Peninsula at 211,720,000 h.p., the Brahmaputra at 402,000,000 h.p. and that of the islands of South-East Asia, Ceylon, Sundra, New Guinea, Celebes, Borneo, Philippines, Formosa, and Hainan at a total of 670,000,000 h.p. The Yangtze and the Brahmaputra each offer a potential water-power greater than that of the whole of Europe, while that of the South-East Asian islands is two and a half times that of Europe.

The most striking single feature of all is the water-power of the Congo and Niger basins in Africa. These together have a greater theoretical potential than the whole of the U.S.A.

The present total world production of water-power is about 134,000,000 h.p. If Asia harnessed only 1 per cent of her theoretically usable water-power, she would have nearly twice as much as the U.S.A. has at present. If Africa harnessed 1 per cent, she would have more than the U.S.A. has at present.

The combination in Asia of vast populations with great potential water-powers is particularly significant for the future of mankind. The constructions required for adequately harnessing the water-powers of Asia and Africa are so vast that they can be accomplished only by the organized effort of whole peoples.

Very big hydroelectric developments are being carried out at present in the U.S.S.R., where the planned development of large regions of the country, which contains great rivers such as the Volga and the Don and the Amu Darya (Oxus), offers immense opportunities for hydroelectric constructions.

The first, and still one of the biggest and most striking of hydroelectric developments centred on the Niagara Falls. Today, about 1,500,000 h.p. is generated by the stations in the neighbourhood of the Falls, and electricity is transmitted to users more than 200 miles away.

On the Canadian side, the Niagara stations are incorporated in the publicly-owned Hydro-Electric Power Commission of Ontario. This controls 64 hydroelectric stations, including many on other rivers, such as the Des Joachims plant on the Ottowa River, and six fuel-burning plants, such as those at Toronto Harbour and Windsor. The total

generating power of the Ontario organization in 1950 was 3,659,920 h.p. It supplied users over almost the whole of Ontario, which covers 363,282 square miles, including 1,132 municipalities, and 1,200,000 individual customers.

TURBINES AND WATER-WHEELS

Broadly speaking, power is obtained from water by two types of machines, and the one chosen depends upon whether a high or a low fall is available. In the former case a Pelton wheel is used. From Plate I*a* it will be seen that this consists of a disc mounted on a shaft, having a number of cups fixed round the edge. These are known as buckets, and they have a ridge in the centre which splits the jet as it impinges upon them. The surface is so shaped that the water glides round without splashing and runs out at the lower edge. When the water issues from the jet it has a velocity which depends upon the height of the surface above the wheel. If the wheel were prevented from rotating the water would have its velocity reversed owing to the shape of the cups, and by virtue of this velocity it would still be capable of doing practically the same amount of work. If again the wheel were to rotate so that the velocity of the buckets was equal to that of the jet, no work would be done on the wheel. Now the greatest efficiency will be obtained when the water falls from the buckets with all its original velocity taken out of it, and this will be the case when the buckets move with half the velocity of the jet. For the water will be flung back at a velocity which just balances the difference between the velocities of the jet and the buckets, and will fall exhausted into the well below.

There must therefore be a definite relation between the height of the fall and the speed of the rim of the wheel. If low speeds are required then a large wheel must be used, but if high speeds are desirable a smaller wheel may be employed. With a large volume of water two or occasionally three jets may play upon one wheel, or two wheels may be fixed side by side on the same shaft. They are made so small as to give no more than 1/5 h.p., and so large as to give 75,000 h.p., as in the Big Creek 2A plant, California, with a head of 2,350 ft. All along the Pacific coast the streams which run from the watersheds of the Sierra Nevada have been harnessed for many years. Originally the water here was used for 'placer' mining. Gold, for example, occurs in loose sand and gravel, and the miners constructed canals high up on the hillsides, which were fed by streams from the winter snows. From these canals the water was led through pipes and the jet was directed against the loose gravel of the lower slopes. The gold and sand were then separated in troughs of running water in which the heavier metal settled, and the earthy material was washed away.

Incidentally this locality was the birthplace of the Pelton wheel. The buckets or cups used on the rim of the earlier wheels were single—they had no central ridge. A carpenter named Pelton engaged in repairs noticed on one occasion that a wheel became displaced so that the jet struck the edge of the buckets. He observed that the water falling on the inner edge curved round the surface with less splashing than in the ordinary wheel, and that the wheel ran faster. So he constructed the wheel with divided buckets which now bears his name.

Where the fall is low or very large quantities of water have to be dealt with, the Pelton wheel is replaced by a turbine. This is a wheel with curved blades, enclosed in a casing. The water usually enters at the circumference of the latter, is deflected upon the blades by guides, and discharged at the centre. The double-vortex turbine is the parent of all inward-flow turbines of today. The blades on the wheel lie across the path of water on its way to the centre and freedom, and are elbowed to one side, thus causing the wheel to rotate.

Inward-flow turbines were first designed scientifically by James B. Francis in America in 1849. The water flows first along a radius of the machine, and emerges along the shaft. The blades turn the water through a right angle, and in doing this take to themselves nearly all of its energy (Plate III*a*).

Francis turbines are now very widely used. The largest in the U.S.A., in the power house of the Grand Coulee Project on the Columbia River, each develop up to 175,000 h.p. Francis turbines are preferred for medium heads of a few hundred feet.

Kaplan turbines for working on low heads (they can be operated in heads measured in inches rather than feet) have movable blades, which can be adjusted to give a high efficiency over a wide range of loads. The lower the head, the bigger the machine. The largest turbines to be found in America are of the Kaplan type, with runners 23 ft. 4 in. in diameter, operating on a head of 69 ft., and developing 74,000 h.p.

The principles of impulse and turbine wheels are both inherent in the ancient Indian water wheel, which consisted of a vertical shaft bearing four square blades, a horizontal stream of water being projected against them from a pipe or channel.

The first great hydroelectric plant was built at Niagara Falls, where nature had provided a great power in a convenient form and place. Several plants are now diverting a tiny fraction of the upper river through their turbines and discharging it below the falls, without appreciably diminishing their grandeur. The Niagara River forms the spout through which the surplus waters of Lake Erie overflow into Lake Ontario (Plate II). In the 36 miles of its length, it falls through 326 ft., of which 216 ft. is in the falls and the rapids above them. Where the latter commence, about half a mile from the edge of the cliff, the river is

divided into two portions by Goat Island, giving a fall 1,000 ft. wide on the American side, and the famous Horseshoe Fall 2,600 ft. wide on the Canadian side. The American fall is 167 ft. high, while owing to the rapids which occur chiefly on the Canadian side of Goat Island the Horseshoe Fall is about 8 ft. less. The quantity of water pouring over these two lips is almost incomprehensible. It has been estimated at 222,400 cubic feet per second, or nearly a cubic mile a week. Expressed in units of weight and power, this represents 22,000,000 tons an hour, and is equivalent to 5,000,000 h.p. In its descent from Lake Erie to Lake Ontario the total energy expended by the river is about 8,000,000 h.p. (Plate II).

Some idea of the importance of Niagara Falls as a centre for the production of power may be gathered from the distribution of the population of the two countries between which they lie. Probably few realize from their school study of Geography that if a circle 500 miles in radius be struck from Niagara as a centre, this circle will include three-quarters of the population of Canada, and half the population of the United States. For it encloses Toronto, Ottawa, Montreal, and Quebec; New York, Philadelphia, Washington, Pittsburg, Detroit, Cincinnati, Chicago, Milwaukee, and Buffalo. The area includes a network of railways, including five trunk lines, the Erie Canal, and all of the Great Lakes except the western half of Lake Superior.

One of the largest installations which tap the vast resources of the Niagara River is the Ontario Hydro's Queenston-Chippewa plant, re-named the Sir Adam Beck-Niagara G.S. No. 1 in 1950. Constructional work was commenced in 1902, and power was first supplied in 1905. The plant was completed in 1930 (Plate I*b*).

Water is taken from the river at a point on the Canadian shore, about a mile above the crest of the Horseshoe Fall, and just above the rim of the first cascade of the upper rapids. The intake works consist of a dam nearly 600 ft. long stretching out in a down-stream direction nearly parallel to the main current; and a submerged wall or dam connecting the outer end on the intake with the shore. Water enters through twenty-five openings in the intake dam, situated 9 ft. from the surface, and extending to the bottom of the river, which is here 15 ft. deep. The floating debris and ice is mostly deflected by the upper portion of the intake dam, and water from the bottom of the river only is taken.

In the comparative calm of the outer forebay any ice or debris which has crept beneath the barrier from the turbulent river beyond, rises to the surface and is either washed away over the submerged wall or trapped by a concrete curtain at the screen-house, which hangs 5 ft. below the surface. The area of the outer forebay is 8 acres, and its depth is from 15 to 20 ft. The inner forebay has an area of 2 acres and

a depth of 20 to 30 ft. In the tranquil waters of this basin the last remnants of floating material rise to the surface and are prevented from passing to the pipe lines and turbines below.

The power station is situated at the foot of the cliff on the Canadian shore just below the falls and is a solid concrete structure with walls from 9 to 12 ft. in thickness. The water is first led through three conduits laid under the Queen Victoria Park until it reaches a point on the cliff above the power house 6,000 ft. away. One of these conduits is 18 ft. in diameter, consisting of a steel tube covered with concrete, and terminating in an overflow chamber through which surplus water can escape by a spiral tunnel to the lower river. Another has the same sectional area but is oval in shape, having a horizontal diameter of 19¼ ft., and a vertical diameter of 16½ ft. It is built entirely of ferro-concrete—that is, of concrete having steel bars embedded in it—and consists of a shell 18 in. thick, strengthened by a continuous saddle. This conduit terminates in a circular concrete surge tank 75 ft. in diameter, which serves to store excess of water when the load on the turbines is reduced. If some plan of this kind were not adopted enormous forces would be developed by the sudden stoppage of thousands of tons of moving water. The tank serves the additional purpose of supplying water to the turbines when that in the conduit is just beginning to move.

Beneath the lower ends of the conduits near to the overflow chamber and surge tank, are valve chambers carved out of the solid rock and having arched concrete roofs to support the conduits. These chambers are about 300 ft. long, 10 ft. high, and 16 ft. wide. Here the water passes through valves into the penstocks or steel tubes 9 feet in diameter, which convey it to the turbines. Each valve is operated by a 30 h.p. electric motor which opens or closes it in four or five minutes.

The power possessed by this mass of water filling the two conduits over a mile long and moving with a velocity of 12 to 15 ft. per sec. can hardly be realized, and water pipes 9 ft. in diameter are outside the range of ordinary experience. To absorb this power the turbines and dynamos must be enormous, especially as the fall is not more than, say, 190 ft. Far smaller machines are possible where a great head of water is obtainable, because a higher velocity is attained by the water in its descent. The Sir Adam Beck No. 1 plant produces 525,000 h.p. Beside it, the Sir Adam Beck No. 2 plant is in construction, due to be completed in 1954. It will produce 700,000 h.p., so the two stations together will produce 1,225,000 h.p.

Power from Niagara is provided for the electric furnaces employed in the reduction of iron, copper, and other ores, and the manufacture of cement, calcium carbide, nitrate of lime, carborundum, and graphite, in Port Colborne, Welland, Niagara Falls, Thorold, and Chippewa, Ontario; and Lockport, New York. The transport systems in Syracuse,

Rochester, Canadaigua, Geneva, Lackawanna, and Hamburg, and the inter-urban railways, Syracuse, Lake Shore and Northern, Syracuse and South Bay, Syracuse and Auburn, Rochester and Syracuse, Rochester and Geneva, Rochester and Mt. Morris (Erie Railroad), Buffalo, Lockport, and Rochester, Buffalo and Hamburg, and Buffalo and Lake Erie, are operated wholly or in part by the power from this centre.

But this is only half the tale. The electric current from the same source drives the machinery of the Canadian Steel Foundries at Welland, and of the Lackawanna Steel Company. It turns the rolling mills of the Seneca Iron and Steel Company, pumps the water at Depew and Lackawanna, supplies the repair shops of the New York Central and Hudson River Railway, and the Delaware, Lackawanna and Western Railroad Company, crushes stone and grinds lime at Akron, Pekin, and Oakfield, and runs the shops of the American Locomotive Company at Dunkirk. For 300 miles east and west, and over 100 miles north and south, the transmission lines radiate, carrying the latent power vested in a tiny fraction of the waters which thunder through the rocky gorge in their passage to Lake Ontario, the St. Lawrence, and the sea.

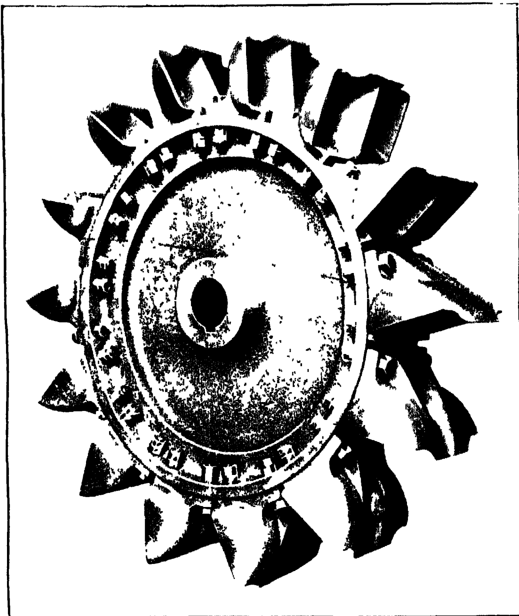
The enormous hydroelectric power produced at Niagara has been paralleled by the huge installations in process of completion at the Grand Coulee Project on the Columbia River in the U.S.A., at Kuibyshev on the Volga, and in other places (Plate III*b*).

The Kuibyshev project, which will be completed in 1955, will then have an output of 2,680,000 h.p., the largest single plant in the world. The dam will be 3½ miles long and 100 ft. high, and will raise a lake 310 miles long, and about 25 miles broad. It will involve moving twice as much earth as in building the Suez Canal. Another station, almost as big, is being built at Stalingrad. The complex of works, of which this is a part, involves three times as much earth work as in the construction of the Panama Canal. The turbo-generators being installed in the Kuibyshev and Stalingrad plants are the largest in the world.

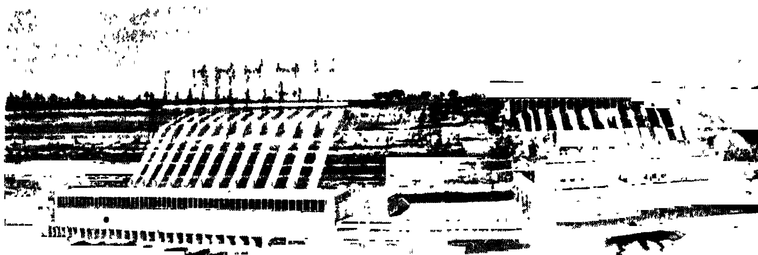
Hydroelectric production has many other merits besides possible vastness of scale. From the point of view of quality of civilization, relatively small water-powers may have high importance in sources of power, such as Switzerland and the Scottish Highlands. The advance of engineering has shown how even modest supplies of water-power, such as those in Scotland, may be effectively utilized.

The North of Scotland Hydro-Electric Board was established in 1943 to undertake all future hydroelectric development in the Highlands and Islands. It has produced schemes for 29 hydroelectric stations containing 56 turbo-alternator sets, with a total horse-power of 844,200 (about half that produced at Niagara Falls).

The largest turbine is of 53,500 h.p. and the smallest is of 268 h.p.



1*a*. The runner of a Pelton wheel



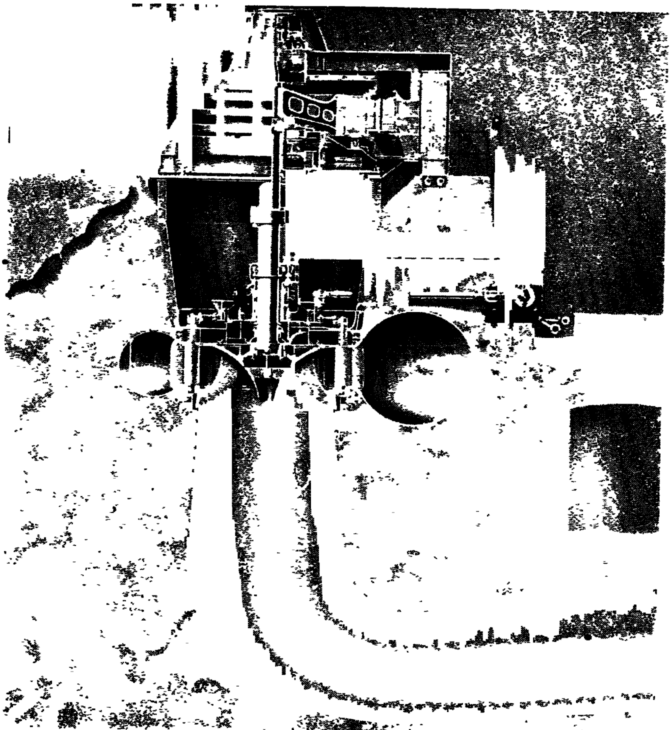
(*Hydro-Electric Power Commission of Canada*)

1*b*. Sir Adam Beck Generating Station No. 1



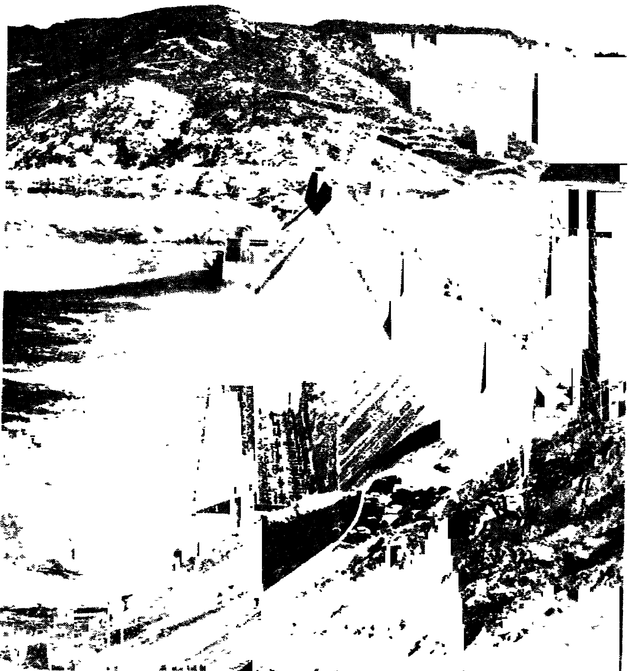
(Hydro-Electric Power Commission of Canada)

II. Bird's-eye view of Niagara Falls



(North of Scotland Hydro-Electric Board)

III*a*. Francis turbo-alternator



(U. S. Bureau of Reclamation)

III*b*. Grand Coulee Project, Columbia River, total capacity 2,604,960 h.p.



(Hydro-Electric Power Commission of Canada)

IV*a*. Interior of Des Joachims Generating Station Power House, on the Ottawa River, 480,000 h.p.



(North of Scotland Hydro-Electric Board)

IV*b*. Loch Sloy Dam in course of construction

Operating heads will vary from 1,362 ft. on the Lawers project near Loch Tay, to 16 ft. at Loch Morar. The Lawers project will have a horizontal Pelton wheel. At Loch Morar two small Kaplan type turbines are installed. A feature of this power station, which is in a beautiful place, is that it is almost invisible.

In the north-west of Scotland there are many isolated communities. A substantial portion of the population is scattered over islands and peninsulae. This difficulty has been met by establishing many small local plants, which may in the future be used to maintain a supply provided by long distance transmission from major sources of power. More than eleven islands which have no water-power have been provided with diesel engine plants, which may in the future be displaced by long submarine cable connections. A Highland Grid of transmission lines operating at 132,000 volts is being constructed.

The project at Loch Sloy (Plate IV*b*) is typical of the variety of the Scottish operations. It is in a wet district near Glasgow, with an annual rainfall of 120 in. A dam 1,160 ft. long and 165 ft. high has been built to collect water, which is run through a tunnel two miles long under Ben Vorlich, to turbines on the edge of the north end of Loch Lomond. The head is 910 ft. Four turbines of the Francis type, running at 428 r.p.m., each develop 46,000 h.p. The plant is run intermittently to relieve the periods of peak load on the electricity supply for Glasgow. Power for auxiliaries and local needs is provided by a Pelton wheel developing 600 h.p.

The power station is quite inconspicuous, so that Glasgow is helped with electricity without spoiling the beauty of Loch Lomond of which she is so proud.

At Lochalsh the Board has built a dam and plant which supplies by submarine cables the south-east district of the island of Skye, the southern side of Loch Duich, and the north side of Loch Carron. In the Tummel-Garry project a dam in Glen Errochty collects water which is discharged through a tunnel five miles long to the Errochty Power Station on the shores of Loch Tummel. The level of Loch Tummel is raised 17 ft. by the Clunie Dam. A tunnel nearly two miles long conveys water to the Clunie Power Station, which in turn discharges into the Pitlochry Dam. The total output of the complex will be 196,980 h.p.

Gairloch, Loch Fannich, Cowal and the Islands of Bute, Loch Benevean and Loch Affric, Glen Lussa and the Kintyre Peninsula in Argyll, Glen Shira, Storrs Lochs in the remote north-east of the Island of Skye, the River Gaur, the Glascarnoch—Luichart—Torr Achilty project, the projects of Moriston and Garry, will all in the future bring power as well as beauty to Scotland.

The Board is furthering research in the generation of electricity by large windmills, and is building a 134 h.p. plant to be driven by a big

windmill on Costa Head, Orkney. It is hoped that this experiment will lead to the successful design of windmills developing some 2,500 h.p. for driving dynamos. It is possible that at least as much energy could be obtained from the winds blowing over Britain as is available from the whole of the potential water-power supply. The quantity of energy in the winds is enormous, and advances in aerodynamics have enabled far more efficient windmills to be designed.

Besides encouraging research in this direction, the Board has placed its reservoirs at the disposal of fisheries investigators, and is giving special attention to the artificial fertilization of waters in order to increase trout productivity. The mineral resources and raw materials of the Highlands are being investigated in order to see whether they can be utilized in new electrical industries. The de-watering of wet materials, such as peat and diatomite, is being investigated by electrical methods.

The hydroelectric development of the Highlands is not grandiose, but it provides an interesting example of how such developments can raise the amenities, conditions and culture of a fine human population, without damaging the famous national heritage of scenic beauty. The values which hydroelectric power can bring to the Highlands are by no means to be assessed by mere magnitude, and this is true for many other regions of remarkable peoples in countries which lack easy sources of power.

In these examples we see an approach to the ideal arrangement of centralized production of power, to which reference will be made from time to time throughout this volume. Incidentally, it will be clear, that the term cheap water-power is liable to be misunderstood, for there is usually a vast expenditure to be undertaken in dams and pipe lines before the energy of falling water can be profitably utilized. But so far it is the only source of power which is reasonably constant, and the use of which does not lead to exhaustion of natural capital. Moreover, with improvements in the production and transmission of electricity, and the discovery of new methods of manufacture in which electricity is the prime agent, a new era has arisen in which industrial prosperity is no longer dependent upon or measured by the price of coal. During the next hundred years the areas in which manufacturing industries are congregated most thickly will not only be situated upon the coalfields, but also in those districts where water pursues its most vigorous progress towards the sea. And the beautiful places on the earth formerly known only to the tourist, the simple shepherd, or the hunter, will have their fastnesses invaded, and their silence, broken now only by the roar of the waters, will reverberate softly to the hum of the turbine wheels.

II

FUEL

THE extent to which all manufacture and transport, and all businesses, are paralysed during a coal strike is an indication of the complete change which has come over the conditions of life within the last two hundred years. A temporary stoppage of the supply of fuel throws all the machinery of existence out of action, and reveals the magnitude of the debt which civilized nations owe to the men who win precious fuel from the earth's storehouse.

THE PERILS OF THE MINE

Hardly any industrial operation excites an interest so fluctuating as that of mining. Carried on, for the most part in districts remote from the larger towns, by men who spend a third of their lives underground, it is a case of 'out of sight, out of mind'. A man or two may be buried beneath a falling roof, or mangled by a runaway train without comment; but every now and then the world is startled by an appalling disaster in which scores of men lose their lives. And so, from early days, when industry began to cry out for more and yet more coal, inventors have been busy devising all sorts of methods and appliances for the prevention of accidents. The Davy safety-lamp, familiar to all, is the parent of scores of others, the fruits of widening knowledge and lengthening experience; and in a hundred ways the perils which beset the miner have been met and countered. But in spite of all, disastrous explosions still occur, though with far less frequency than if the only precautions were those of even fifty years ago.

These explosions are due to a gas called marsh gas, or fire-damp, having the formula CH_4. It is inflammable, violently explosive when mixed with air and ignited, and is given off in large quantities from many varieties of coal. Naked lights may be used where no gas is evolved. There are about 1,300 mines in Britain. Only about 200, scattered in the Forest of Dean, Scotland, Northumberland and

Durham, are naked light pits. The tendency is to make all pits into safety mines. But all mines must be ventilated by forcing or draining air through them with a fan, and the quantity of air must be sufficient to keep the percentage of gas below a dangerous level. The mine is 'examined' at regular intervals by the 'Fireman' or 'Deputy' who can estimate approximately the percentage of gas present by the size of the faintly luminous 'cap' which hovers above the flame of his lamp. This depends upon the size of the flame, and the necessity for some special training for this work will be apparent from Plate V*a*, which shows the cap over large and small flames. That above at the bottom is due to 4½ per cent and that on the left to 3½ per cent of gas. It will be observed that the smaller percentage gives exactly the same size of cap over the larger flame as the larger percentage gives over the smaller one.

Explosions have occurred, however, in cases in which it is extremely doubtful whether gas has been present in dangerous quantity, and attention has been drawn to another possible cause. Many varieties of coal produce fine dust, which settles in the roadways—on roof, and sides, and floor. For a number of years there has been a controversy as to the relative importance of gas and dust in producing explosions. But there is no doubt that a mixture of coal-dust and air is explosive, and that even if an explosion is started by gas the disturbance creates clouds of dust which cause secondary explosions and spread the disaster over a wider field than was originally affected.

Consequently the rules of the Ministry of Fuel and Power require the roadways to be treated to keep the dust from rising. More inspectors have been appointed, and Firemen, or Deputies, whose duty it is to visit the workings and report the presence of gas or defects in the ventilation, are required to possess a certificate of competency. The spreading of fine stone-dust in the roadway is compulsory. This becomes mixed with the coal-dust and renders it less explosive.

Unfortunately the disastrous effects of an explosion do not end with the explosion itself. The chief products of combustion of fire-damp or coal-dust are carbon monoxide, CO, and carbon dioxide, CO_2. The second of these causes suffocation; the first is a poison. It is the dreaded 'after-damp' of the miner. Those who survive the explosion are therefore in imminent danger and it becomes imperative to restore the ventilation with the least possible delay. For even if the fan, which drives air through the workings, has escaped injury, falls of roof may have blocked up some of the roadways, or the explosion may have torn down doorways and provided a short cut for the air. But if it is dangerous for men in the pit at the time, it is equally dangerous for others to go down and effect repairs or render first aid. The work of the rescue party is therefore a labour of desperate heroism, and not infrequently attended by additional loss of life.

It has been found possible to reduce the danger to which members of rescue parties are exposed by providing them with self-contained

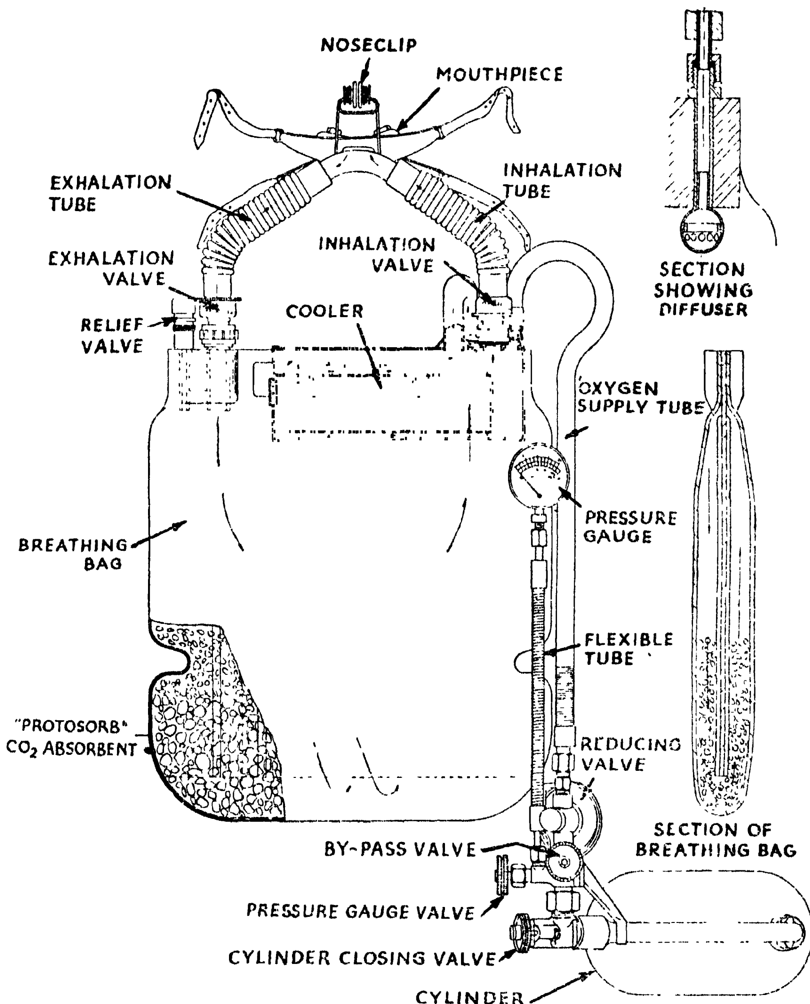


Figure 1. Diagrammatic view of the single cylinder two-hour 'Proto' Mark IV breathing apparatus (Siebe, Gorman)

breathing apparatuses which fit over the mouth and nose. The wearer is supplied with oxygen from a steel cylinder strapped across his back, and the way in which the appliance is constructed and works will be

easily understood from Fig. 1 and Plate V*b*. The bag in front contains 'protosorb', a mixture of lime and caustic soda, which absorbs the carbon dioxide produced during respiration. The cylinder contains about 10·5 cubic feet of oxygen gas, which is sufficient for two hours' strenuous labour.

In all the important colliery districts special rescue stations have been established. These are buildings in which small groups of men can be trained in the kind of work they may be called upon to do, and in such an atmosphere that would be produced by an explosion or a fire in the mine. There are now thousands of men accustomed to wearing the apparatus, able by its aid to penetrate smoke and foul air, remove any who have been overcome, and effect such repairs as may be necessary to restore ventilation.

THE GASIFICATION OF COAL

Coal, burnt in ordinary grates, is not a very economical fuel, and it is less wasteful of its valuable volatile constituents to convert it into gas. The production of gas by heating coal in fireclay retorts is, of course, a century old, but the gas obtained in this way is chiefly valuable as an illuminant and the coke left in the retorts has limited use as a fuel.

An economical way of obtaining gas from coal is by means of the gas producer. It consists of a cylindrical furnace which is charged with coke, or with anthracite coal which contains a high percentage of carbon. Air is admitted at the bottom, where the oxygen immediately combines with the carbon, of which the coke is mainly composed, to form carbon dioxide, or CO_2. In its upward passage the carbon dioxide reacts with the red hot coke to form carbon monoxide, CO, which will burn in air with a very hot flame. Producer gas has, however, a low calorific value or heating power, owing to the fact that four-fifths of the air which is admitted to the furnace consists of nitrogen. A product of greater heating power is obtained by using steam instead of air, when a mixture of carbon monoxide and hydrogen is obtained. Unfortunately, the steam lowers the temperature of the furnace and the only way to keep up the supply is to force steam and air in alternately. Water-gas, as the mixture of carbon monoxide and hydrogen is called, is frequently made in this way for mixing with rich coal-gas; or is itself enriched with oil-gas and used instead of coal-gas. When the furnace is blown up by air, the gas, being chiefly carbon dioxide and nitrogen, is allowed to escape, and the intermittent working of this producer has been against its wider adoption.

By using air and steam together the temperature of the furnace can be maintained and the semi-water-gas contains hydrogen and a lower percentage of nitrogen than producer gas.

But these producers require either coke or anthracite, and while the former is cheap only to the manufacturer of town gas, who obtains it as a by-product, the latter is a very expensive fuel. Consequently, when Ludwig Mond invented, in 1889, a process which would work with

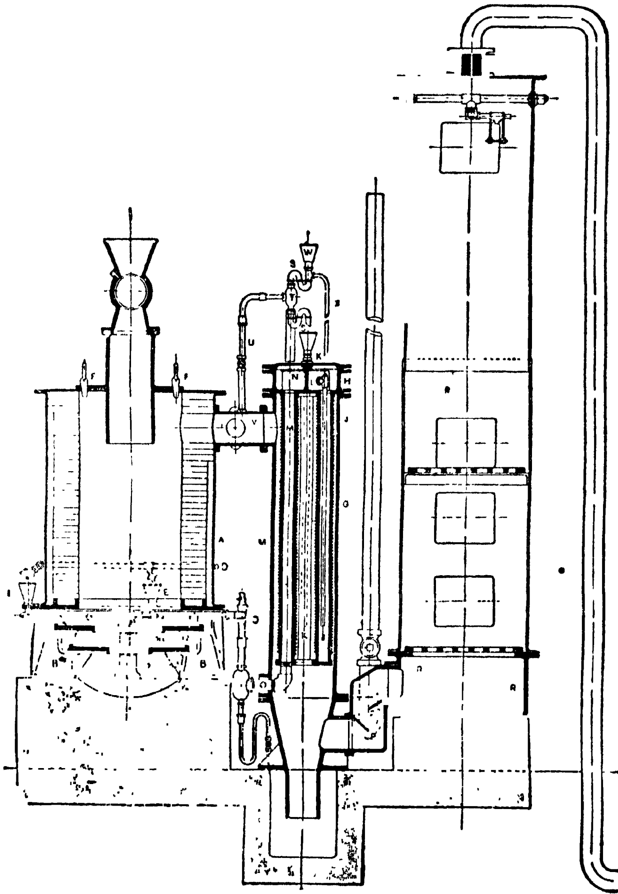


Fig. 2. Section of gas producer

cheap coal-slack, another step in economy was taken. But the advantage of the process did not rest entirely upon the cheapness of the fuel, for the use of coal instead of coke, and the use of a large quantity of steam —2½ lb. for each lb. of coal consumed—enabled ammonia to be obtained as a by-product. Only one-fifth of the steam goes to form

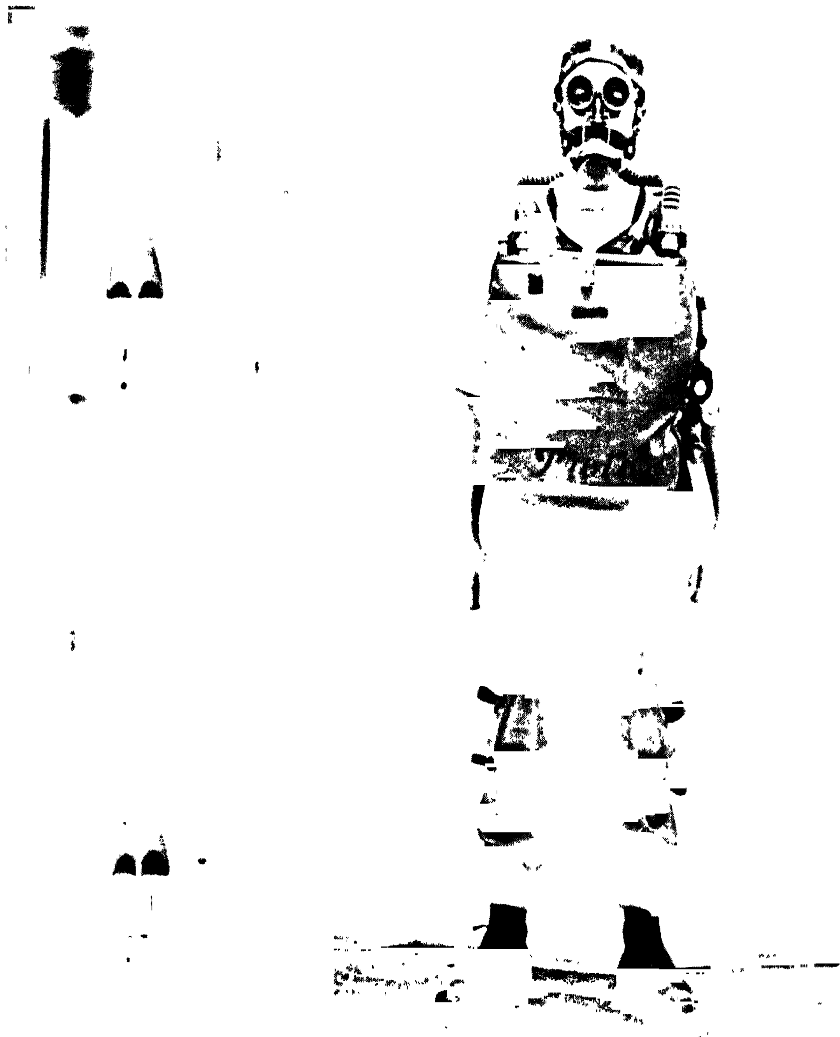
carbon monoxide and hydrogen, but the excess served to keep the temperature low and increased the production of ammonia to 80 lb. a ton, whereas the ordinary gas-works process yielded only 30 lb. a ton. Further, the excess of steam was used to warm the incoming air, so that the heat in that which escaped was not entirely wasted.

In places where coal is dear or unobtainable, a gas producer can be constructed to work on sawdust, wood refuse, rice husks, olive-oil residues, tannery refuse, cotton seed, mealie cobs, or any other waste material that is available.

Pulverization provides another way of using coal which secures uniform and rapid combustion under complete control. The fuel is pulverized, dried, and supplied to the furnace by a blast of air. During the last thirty years this method has been developed greatly for raising steam in boilers. It enables small coal, which is hardly suitable for any other purpose, to be used, and it possesses most of the merits of a gaseous fuel.

Let us now review the various methods of using coal. Firstly, it may be burnt in a raw state, either in lumps or in a pulverized condition. By this method all the by-products—ammonia, tar, benzol, etc., are lost. Secondly, it may—indeed, some of it must—be converted into metallurgical coke, producing gas, and permitting the by-products to be collected. Thirdly, it may be converted into town gas, with production of household coke or semi-coke, and recovery of the by-products. Fourthly, it may be converted wholly into gas with recovery of by-products. The first method is the least and the last method the most economical. But metallurgical coke is necessary, many people prefer to use solid fuel, and gas-works coke is relatively cheap and can be used where hard metallurgical coke would be impossible.

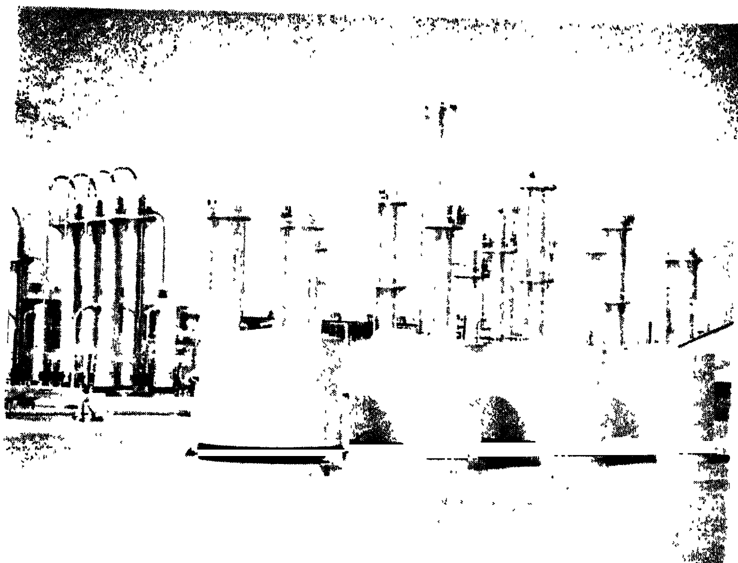
But the general tendency must be in the direction of economy. The large super-power stations which are being built consume enormous quantities of raw coal. They convert only about 25 per cent of the energy in the coal into useful work. A gas engine converts 30 per cent, but there are mechanical difficulties of constructing these engines of large size. So far as large scale production of power is concerned a country which possesses coalfields must continue for the present to use raw coal. A large power station is much more economical than a small one. But the use of raw coal for domestic purposes should be minimized. The black pall that hangs over thickly populated manufacturing districts would disappear and the grime of the city would be greatly reduced, if the open grate with its smoky chimney and its ashes would give place to the closed slow-burning stove. Labour would be saved, life would be cleaner, brighter and healthier than it is today, and the country's irreplaceable coal resources used and conserved with far greater efficiency.



(Siebe-Gorman)

V*a*. Flame caps on a miner's lamp

V*b*. Proto Mark IV breathing apparatus (front view)



(Petroleum Information Bureau)

VIa. Fractionating columns in a distillation unit near Houston, Texas



(Petroleum Information Bureau)

VIb. Three catalytic cracking plants at the Baton Rouge Refinery, Texas

THE STORY OF OIL

Mineral oil is today so common and has such a variety of uses that we are apt to forget how recently it has been discovered in large quantities or how rapid has been the growth of its production. For centuries 'rock-oil' has been collected as it oozed from the ground; but the quantity was so small that practically the whole output was consumed in the locality, and people remote from oil-bearing strata fed their lamps with fuel from animal or vegetable sources. The discovery that petroleum could be obtained in more generous measure from deep underground reservoirs was made by Colonel Drake who, in 1859, sunk a well at Oil Creek in Pennsylvania. The first cargo reached London in 1861, and the annual output of 1,000,000 tons rose to 9,000,000 tons in 1891—all from Pennsylvania and Ohio. The charges made by carters and railway companies became so exorbitant as the industry flourished that long lines of pipes were laid from the oilfields to the ports, and special tank steamers (see p. 309) were built into which the oil could be pumped from the terminal reservoirs. These were followed by tanks mounted on railway trucks and road vehicles, so that small consumers could buy oil which had been conveyed in bulk almost to their doors.

The extraordinary success of the Pennsylvania fields and the development of the oil and petrol engines encouraged prospectors to search for other oil-bearing areas. Oil-prospecting has been continued with ever-increasing completeness over the North American continent. Latterly, large new oilfields have been developed in Alberta, Canada. Immense fields have been developed in the U.S.S.R., the Middle East, South America, and in other regions. Great Britain has very little oil and is dependent upon the product of other countries.

Petroleum occurs in certain porous layers of the earth's crust, just in the same way that water collects in porous sandstones. It frequently contains in solution gaseous substances, so that when the well reaches the required depth the oil is forced out in a fountain several hundred feet high. Some 'gushers' pour out thousands of gallons a day for weeks or months after they are first tapped, but the pressure gradually decreases until the oil has to be pumped to the surface. As thus obtained it is an evil-smelling liquid, varying from colourless through shades of brown to black. It differs in composition in different localities, and there is a corresponding variation in the methods of purification and the products obtained.

The crude oil is a mixture of many hydrocarbons, or bodies consisting of hydrogen and carbon. Some of these are light, highly-inflammable liquids, which become gaseous at the ordinary temperature; others are heavier, but still inflammable liquids; others are yet heavier liquids,

thick and treacly in appearance, less inflammable, but of great value for lubrication; while still others are greasy or waxy solids at ordinary temperatures. Each of these is suited to its particular purpose, and the method of separation is based upon the principle that every pure substance boils at a definite temperature under a given pressure. If, therefore, a mixture like crude petroleum is heated, the constituents of lower boiling-point distil over first, and if the receiver in which the liquids are collected is changed from time to time, fractions boiling between certain limits of temperature are obtained.

Several methods have been employed. In the old original one, the vessel containing the crude oil is heated gradually and as the lighter liquids pass off the temperature in the still rises. The vapours are cooled by passing through several hundred feet of pipe, over which cold water flows, and ultimately run into a receiver which can be changed as occasion requires. In practice, the actual temperature was not observed. The distilled oil flows into a box with glass sides, and the man in charge can tell from the appearance and rate of flow when oil is to be directed into a fresh receiver. The oil is dealt with in 'batches' and the process is intermittent.

The process may be made continuous by pumping the oil in succession through a series of stills of successively higher temperatures. Passage through the first causes the oils of lower boiling-point to evaporate; passage through the second separates the group of substances having a higher boiling-point, and so on. With the first process the best yield of illuminating oil is obtained, and with the second the best yield of lubricating oil.

The products, in the order in which they are obtained, are as follows:

1. Gases—solidifying near the freezing point of water.
2. Clear, colourless light oil—naphtha.
3. Yellow illuminating oil—kerosene or paraffin.
4. Lubricating oils.
5. Paraffin wax.
6. Coke, pitch or asphalt.

The gases which come off first are allowed to escape into the air, or are used to heat the stills. The naphtha is redistilled and gives

(*a*) Gasolene or petrol.
(*b*) Commercial naphtha.
(*c*) Benzine.

The first of these is the substance so largely used in the engines of motor-cars and aeroplanes. The last is used for dry-cleaning, and should not be confused with benzene, a coal-tar product which is sometimes used for motor-cars owing to the present high price of petrol. A similar process of redistillation can be applied to the illuminating oils by which the different qualities are separated (Plate VI*a*).

The lubricating oils and the paraffin wax both are further refined before they come on the market. The high speeds, high pressures, and high temperatures employed in modern engines have imposed severe conditions upon the oils which are required to reduce friction, and the separation of these into grades suitable for different purposes has become a fine art.

Before considering the special use of oil as a fuel it will be interesting to glance at the great variety of services which petroleum products render to mankind. Of the hundreds of substances that have their origin in raw petroleum, the illuminating oils have surely the oldest interest. In all the far corners of the earth, where the advantages of town life do not exist, they add to the light of day and well-nigh double the hours which man can give to his labours. They supplement the beams of the Arctic moon, and dispel the gloom of the tropical night. They illuminate the sick-room and diminish the terrors of darkness. In a thousand and one ways they contribute to man's comfort, and aid him in his fight against time and circumstances.

The lighter products are valuable solvents for rubber. Cloth may be rendered waterproof by a thin layer of rubber, which, when dissolved in naphtha, can be applied with a brush. As the naphtha evaporates a continuous skin of rubber remains, which is light and impervious to rain. So in a similar way, resins can be dissolved, forming varnishes, which on drying give a bright, hard surface that acts as a preservative of the material upon which it is laid. The readiness with which it dissolves fats and other substances not soluble in water, causes benzine to be used in extracting grease from leather, in dry-cleaning, and in extracting oil from the seeds of plants. It is also used in the manufacture of jute, the fibre that is woven into the coarse canvas or 'scrim', which is so largely employed for packing bales of cotton and other fabrics. Finally paraffin is mixed with water or lime wash for spraying fruit trees to destroy insect pests.

From the heavier samples come Vaseline, which is closely allied to the lubricating oils, petroleum jelly, and similar substances. Paraffin wax, obtained from the heavier varieties by freezing, and purified by six or seven successive processes, is used as an insulator for electrical work, for candles, in the manufacture of matches, for lining barrels to render them water-tight, and—for chewing-gum! Look where you will, and there is some product of petroleum to meet a necessity or provide a comfort. In the future, petroleum may well become more important as a source of synthetic chemicals, than as a fuel.

But as yet most of these substances are by-products, and the enormous activity in the oil industry arises from the value of oil as a fuel. From what has been said about gaseous fuel, it will be apparent that the best way to burn a liquid fuel is to convert it into vapour, or at all events

into a fine state of division. In using oil, therefore, in a furnace or under a boiler it is necessary to convert it into a fine spray, and this is usually effected by forcing it through a special nozzle which breaks it up into fine particles. These form an intimate mixture with the air supply, and when the latter is properly adjusted rapid and complete burning results. The cost of the lighter oils prevents their use for this purpose except on a small scale. The heavier oils, which are cheaper, do not flow freely, and they must be heated and then forced through a nozzle by a jet of steam or compressed air. Such a nozzle is called an atomizer, because it breaks up the jet into extremely fine particles.

The fact that heavy grades of petroleum or even coal-tar can be and are used in this way has had an enormous effect on the oil industry. The Californian oils, for example, are heavy, contain but a small proportion of the lighter constituents, and are not so suitable to refine. The value of the oil from this State therefore depends very largely upon its use as a fuel. In marked contrast oil from Mexico and the East Indies yields a very valuable proportion of petrol.

The special value of a liquid fuel in steam-raising depends upon the fact that the flame immediately reaches its maximum temperature—ignoring for a moment the cooling effect of the furnace. In a coal fire, on the other hand, some time must elapse before it is hot enough to raise steam.

Besides burning it beneath boilers, however, oil is used in enormous quantities in the internal-combustion engines described in Chapter IV, and for the details of its employment in this way that chapter must be consulted. It may, however, be stated here that while formerly the chief demands were for the middle fractions—the illuminating and lubricating oils—the petrol and heavy oil engines have created an enormous market for the lighter and heavier products respectively. Moreover, it should be noted that while America produces more than half of the world's supply, it is not the only country which sends oil to Great Britain. Large quantities come from the Middle East, and other countries.

For burning under boilers and in the Diesel engine crude grades of heavy oils, and even tar, can be used; and these are obtained by distilling oil shales and coal. So we are by no means entirely dependent upon oil wells for oil fuel. It must be remembered that the world resources of oil are far less than those of coal.

PRODUCTION OF PETROLEUM

There have been spectacular increases and decreases in petroleum production in various countries in recent years. Examples of these are given on the opposite page based on figures supplied by the Petroleum Information Bureau.

PRODUCTION OF PETROLEUM IN CERTAIN COUNTRIES
(in units of 1,000 metric tons)

Country	*1951*	*1950*	*1938*
U.S.A.	324,000	285,000	170,700
Venezuela	90,900	79,800	28,100
Saudi Arabia	37,100	26,600	100
Kuwait	28,200	17,300	—
Iran *	16,400	32,300	10,400
Mexico	11,000	10,300	5,500
Canada	6,400	3,900	900
British Borneo	5,000	4,200	900
Qatar (Arabia)	2,400	1,600	—
Egypt	2,400	2,400	200

* Production during period January–July 1951.

Particularly striking among these figures are the very big increases in Kuwait and Saudi Arabia in the Middle East, and in Venezuela in South America.

The Petroleum Information Bureau estimates the world production of petroleum in 1951 as exceeding 600,000,000 metric tons, compared with 280,500,000 in 1938.

THE MODERN OIL REFINERY

The Petroleum Information Bureau, to whom we are indebted for the following information, has pointed out that probably no group of essential products have had greater prominence paid to their importance during the years following the Second World War than have the finished products of petroleum, or crude oil. Nor is this surprising; for without these numerous derivatives, the majority of contemporary industries would find their daily activities immeasurably harder, if not impossible, to carry out. Oil supplies are, indeed, among the main foundations upon which modern civilization and standards of living have been based. Yet crude oil as such, except for an ancient cure for Camel's mange, is of comparatively little value. Before it can fulfil its role in present-day commerce, it must be converted into its numerous finished forms.

This is accomplished by refining. Oil refineries are among the most complex plants serving any enterprise today. A few figures may prove of interest to illustrate what is represented in terms of material by a typical large modern refinery—one of the new plants just built in the United Kingdom as part of the refinery expansion programme. This plant absorbed 112,000 tons of steel, 30,000 tons of cement, 17,000,000 bricks, 600,000 cubic ft. of timber, plus a host of other assorted constructional requisites. When in full production, its running will entail

provision of 600,000 lb. of steam an hour—sufficient to drive the Royal Scot express train 1,200 miles—and 3,500,000 gallons of cooling water hourly. While its current consumption—14,000 kilowatts—would satisfy the needs of quite a sizeable town.

Such plants often cover sites of 500 or more acres—and the cost of their equipment may represent a capital investment of £35 million, or more. Together with their tanker docks, railway sidings, power generating stations and other installations, they are among the most self-contained of large industrial units. Now, suppose you were to be invited to make a tour round one such installation—what would you find on arrival, where would your guide be likely to take you first?

Almost certainly, your first inspection would be of the plant's distillation unit, the hub of the refinery through which all incoming crude oil must pass. Distillation is the basic principle underlying the refining of petroleum, the means whereby the various components of crude oil are separated according to their respective boiling ranges by careful control of distillation and condensation temperatures (Plate VI*a*).

This initial unit is carried out in 'fractionating columns' or, as they are sometimes called, 'bubble towers'. These are vertical steel cylinders, ranging from 2 ft. to 25 ft. or more in diameter, and from 40 to 120 ft. or more high. Before being fed into the fractionating column, the crude oil to be processed is preheated to a temperature of around 750° F. in furnace 'still' pipes and then, as part vapour and part liquid, it is passed into the base of the column. The column itself is divided into 'floors' by means of trays in which there are numerous perforations. The hot vapours at once begin to rise towards the top of the column, filtering through the perforations in the intervening trays. The vapours with the highest boiling points condense on the trays at the bottom of the column—its hottest section—and those with the lowest boiling points reach the coolest section at the top. Only gasoline (or petrol as we call it) and any 'fixed gas' flow from the column's summit in vapour form.

To make the sequence of distillation and condensation even more thorough, the perforations in the trays are covered by 'bubble tops'—hence the fractionating column's alternative name—and these bubbles are shaped like huge thimbles and fixed just clear of the tray's floor. Their purpose is to force the ascending vapours to bubble through the condensed liquids on the various trays so that any lighter compounds, which are for any reason still retained in these liquids, are boiled out by the hotter vapours as they rise to the surface. Similarly, any heavy compounds remaining in the vapours which should have been previously extracted are condensed by the cooler liquids. When sufficient liquid has been collected on any one tray, the residue spills into an overflow pipe and flows to the tray below. Here it is again vaporized and the process repeated, each transformation resulting in the 'dis-

tillates' or 'fractions' on the different trays conforming more closely to the type required. These fractions—kerosene (paraffin), gas oil or fuel oil, for instance—can be drawn off from the fractionating column as required.

Here it must be emphasized that the above description is a simplification of the process of initial distillation, for in practice no one single fractionating column could provide the finer degrees of all the different temperatures required. Actually, it is customary to carry out the process of distillation in stages: 'side strippers' receiving the liquids from the trays in the main column for further distillation in smaller adjoining columns—thus further enhancing the efficiency of the separation. Nor are all the various fractions in anything approaching their marketing state even when they have been fully treated at the distillation unit. Very considerable further processing may be necessary before the requisite degree of purity and quality has been attained. Kerosene, for example, requires secondary treatment to render it colourless and to remove all offensive odours, which is done by processing with sulphur dioxide. Lubricating oils, as familiar to all motorists or motor-cyclists, need very extensive secondary processing. After the lubricating oil fractions have been drawn from the distillation unit, they are passed through various other units for de-asphalting and de-waxing and a final filtering. Then blending of the various basic grades will be carried out and any necessary additives, to impart special properties to various lubricants, will be introduced.

But to return to the distillation unit for a moment, one question we are sure to ask our guide, and which has not yet been dealt with, is: what happens to the gasoline that is drawn off in vapour form?

This is led to a condenser where it is liquefied, but some of this liquid is fed back to the top of the fractionating column where it helps cool the rising vapours before being itself transformed into vapour and carried off once more along the gasoline line. Thus gasoline is subjected to quite as rigorous a process of distillation as are the heavier fractions. The whole process of distillation is known as 'continuous rectification', and the thick viscous residue which remains at the base of the fractionating column provides the material from which the various asphaltic products are obtained.

However, though the quantities of the primary products obtained during distillation correspond very closely to the proportions in which they are present in crude oil itself, these quantities seldom correspond with the world's demand for individual products. Motor spirit furnishes perhaps the best example.

It is ironic to think that at one time gasoline was poured away by the million gallons at the early oil refineries and was regarded as a highly dangerous, useless waste product. But the coming of the internal

combustion engine radically changed the situation. As the newfangled 'horseless carriage', the motor-car passed, almost overnight, from a fad to an established method of transport, so the oil industry found itself faced with a quandary. So great was this sudden demand for the hitherto despised gasoline, that either very much more crude oil had to be produced and refined in accordance with then standard refinery technique—thus risking a surplus of other products automatically produced at the same time as gasoline—or else some new method had to be evolved to increase the quantity of gasoline that could be obtained from existing supplies of crude oil.

The oil industry, while expanding its production activities as a matter of consistent policy, nevertheless investigated with energy the problem of modifying refinery processes. And as a result, the technique of 'thermal cracking' was adopted commercially as early as 1913. Briefly, this technique entailed the subjecting of some of the heavier fractions remaining after crude oil's initial distillation to exceedingly high temperatures and pressures (perhaps some 900° F. or more at 50–100 times atmospheric pressure) in a special plant known as a 'reactor'. This treatment literally 'cracked' some of the large molecules of the heavier oils into the smaller molecules of gasoline, leaving a residue of extremely heavy oil. Introduction of this method had another advantage, apart from adding to the gasoline recovered from any given amount of crude oil: it was found that gasoline produced by 'cracking' was of substantially better quality than that obtained by ordinary distillation (Plate VI*b*).

Just before World War II, the principle of cracking was taken a long step further. This was the introduction of catalytic cracking—a term nowadays becoming increasingly familiar in view of the six catalytic cracking plants being built in the United Kingdom. A catalyst is a substance which, when present at a chemical reaction, assists that reaction without itself becoming finally changed. The catalysts used by the oil refineries are mainly compounds of aluminium, silicon, nickel, manganese, iron or other metals, and the catalytic cracking plants themselves are towering erections, several hundred feet high, and not unlike the distillation columns in general outside appearance. The shape the catalysts take varies according to the design of the plant itself: sometimes they are in bead or pellet form, sometimes in the form of so fine a powder that they appear no longer to be solids. But the principle behind their use is the same in all cases. Again, catalytic cracking has been found to possess two advantages: it enables the process to be carried out at considerably lower temperatures and pressures than when heat alone is used, and it leads to an even higher-quality petrol than in the case of thermal cracking.

Moreover, apart from their chief purpose of providing premier motor

spirit, catalytic cracking plants have proved extremely valuable in an entirely different sphere. That is in the properties of the gases given off during the actual cracking process. Intensive research by the oil chemists has shown that these gases contain constituents which have an extraordinary wide range of application as petroleum chemicals. For example, one of the hydrocarbons present in such gases is ethylene, which can be used, among other purposes, (*a*) as an anaesthetic, (*b*) as a ripening agent for tomatoes and citrus fruits, (*c*) as a stimulant for hastening the growth of potatoes. Or it can be converted to glycol, a substance similar to glycerine, and widely used as an anti-freeze agent for motor radiators. It can also be converted into ethylene oxide, increasingly used as a fumigant for cereals and other foodstuffs as well as for tobacco. From another cracked gas hydrocarbon, propylene, are obtained such products as acetone, a colourless liquid used in the manufacture of artificial silk, artificial leather and safety glass, as well as a solvent for the nitro-cellulose required by the film industry. In fact, the cracked gases supply the raw materials for a whole range of supremely important industrial alcohols and ketones which have a very wide range of uses. In the United States, where the production of petroleum chemicals has already become a major enterprise and where hundreds of millions of dollars have been invested in plant for this purpose, such chemicals now account for 25 per cent of that country's entire chemical production, and it has been estimated that by 1962 they will account for 50 per cent. And while not all such chemicals are derived from cracked gases, the availability of the latter has been among the main reasons for the development of petroleum chemical production in the U.S.A. to its present peak. It should be mentioned here that now Britain, too, has an established and rapidly expanding petroleum chemicals industry of her own. As the new catalytic cracking plants in this country make available the raw materials upon which production of many petroleum chemicals depend, so will our own petroleum chemical industry grow in proportion, with the prospect of becoming ultimately an important export enterprise as well as removing the necessity of importing many chemicals now obtained from overseas sources.

So it is understandable why, if you visit an oil refinery, you will probably have the 'cat cracker', as the oil refiners call their installations, pointed out to you with special pride. And in view of the tremendous development which has taken place in the use of the products of 'cat crackers', in a little more than ten years of the technique's introduction, it is easy to understand why this pride exists.

However, while being impressed at the various specialized installations to be found at any sizeable refinery, we should not overlook one unobtrusive, but none the less essential, department that lies in the background. This is the refinery laboratory, which will probably be

divided into physical and chemical wings and which plays a vital part in the whole plant's smooth and efficient functioning.

This laboratory is not concerned with fundamental research into new methods or new uses for new petroleum products: that work is the task of the numerous oil industry research stations maintained in all parts of the world. The oil refinery laboratory deals with the practical day-to-day activities of the plant of which it is a unit. When a new consignment of crude oil is received, for example, the laboratory must first analyse its content and evolve a suitable schedule for its treatment. Crude oils from various fields vary in characteristics just as do, say, marble or diamonds. And just as a sculptor or a jeweller, faced with a new stone for cutting, first studies the graining and all other individual characteristics before planning how to shape or cut the raw material to show off its best advantages, so the refinery chemists decide exactly what proportion of each finished product should be most economically obtained from the crude oil delivered to the storage tanks. This entails close consultation with the refinery accounting staff, who can work out practically to a farthing the estimated results from the sales of the various proposed finished products after deducting the cost of their refining.

But deciding upon a particular schedule is only part of the refinery laboratory's responsibility. It must also conduct constant routine tests of every individual product being processed and ensure that at each successive stage in its treatment the necessary degree of purity and quality is being achieved. Tests for sweetness, sulphur content, wax extraction, and many other important points must be so frequent and exhaustive that there is no chance of variation occurring from the set standard. And everyone who has had experience of an oil refinery will know that the laboratory chemists are rigid taskmasters. They will only accept 100 per cent conformation to specification: 99½ per cent is, to them, not good enough.

One other point which is characteristic of any oil refinery is that activity there never stops. For twenty-four hours a day, seven days a week, and for month in, month out, of every year, the giant installations are kept in operation or, as the oilmen say, 'on stream'. Sometimes, one or other plant will have to be taken out of commission for a few days, after the conclusion of a 'run', for overhaul and cleaning. But when that happens, its servicing or repair is carried out by daylight and darkness without interruption until it is ready for operation once again. As a composite unit, however, the refinery never sleeps. Night shifts take over from day shifts and the oil is kept constantly circulating, just as the ocean-going tankers arrive with almost every tide to unload more crude oil or load up with finished products, and the supplementary road and rail tank wagons keep up a non-stop arrival and departure traffic,

converging on the storage tanks and then veering off to whatever part of the country the finished products are consigned.

As at least 1,000 different petroleum derivatives are used today in processing or manufacture of some 5,000 different commodities, their importance—quite apart from their use as fuels or lubricants for transport or industrial plant—can easily be grasped. Indeed, just as the distillation units of refineries can be called the hubs of these highly specialized plants, so oil refineries have become one of the hubs upon which the wheels of modern commerce revolve. They are also one of the cornerstones upon which our contemporary way of life and standards of civilization have been founded.

ALCOHOL AS A FUEL

The rise in the consumption and price of petrol has led to a search for substitutes especially suitable for use in small motors. This has drawn much attention to the possibilities of alcohol. The fact is that alcohol costs very little to manufacture. Practically all plants contain starch or cellulose—in fact, the latter is their chief constituent—and both starch and cellulose produce sugar either in the natural processes which accompany plant growth, or by artificial fermentation. Further, sugar yields alcohol when the living ferment yeast is grown in it. It is clear, therefore, that while some forms of vegetable life would produce more alcohol than others, this liquid, which will burn and can be used in internal combustion engines, could be obtained in enormous quantity if required.

But the question raised by the use of alcohol is of far wider significance than appears at first sight. Timber is a slow-growing form of fuel, and its use is attended with disadvantages, to which reference has already been made; and alcohol can be prepared cheaply from any kind of quick-growing vegetation that absorbs carbon dioxide from the air to build up the cellulose of its framework or the starch of its cells. This may not appeal very strongly to those who live in thickly populated countries where land is dear and needed for raising food, but it may appeal to the colonial farmer, who sees an opportunity of clothing profitably the vast acres around him.

Coal and petroleum, on the other hand, are not, so far as we know, in process of formation at the present time in any part of the earth's crust, and the use of these kinds of fuel is a continual drain upon capital. The materials which the plants take from the soil can be returned to it, but there is no way of replacing coal in a mine or of renewing the oil in an exhausted well. If in time the ancient store of natural fuel, such as coal, oil, and uranium, should give out, then so far as we can tell now there would remain as the chief source of power, the sun's rays. These

provide the energy which can be got from wind and water, and from such combustible material as can be grown after the demand for food has been satisfied. Intense efforts are being made by the chemists to synthesize chlorophyll, the substance which plants use to capture the energy in sunlight, and the biologists are working on quick-growing small plant and animal organisms, which will use sunlight to produce organic materials and food much more quickly and in vastly greater concentration than they can be grown in spread-out open fields. If these efforts should succeed, then the hot sun-drenched deserts may become the scenes where highly nutritious proteins are synthesized in factories by micro-organisms flourishing under the tropical sun. Such a discovery would completely change the present dependence of mankind on extensive cultivation of the land, and would lead to a fundamental revaluation of the different parts of the surface of the earth.

III

STEAM-POWER

WHEN James Watt, in 1769, improved the crude and clumsy contrivance that worked by steam, he created the new source of power on which the industrial revolution of the eighteenth century developed. In the two centuries which have elapsed since his time the material conditions of life have altered to a greater extent than in the previous 1,700 years. A new civilization has arisen, so different from any which have previously existed in the history of the world that man has hardly yet grasped the significance of the change, and can only see 'as in a glass, darkly', the possibilities of the coming years.

For more than a century the steam-engine had a clear field. The production of power is under more complete control than from a waterfall whose volume varies with the seasons. The great manufacturing towns sprang up on or within easy reach of the coalfields. Knowledge of electricity, the possibilities of which had been seen by Faraday in 1831, passed through a long period of infancy, and by the time that efficient generators of large size were a commercial success the steam-engine was firmly established. Not until after 1876 did the internal combustion engine appear on the scene, and for twenty years it did little more than supplement in a humble way the efforts of the giant that had altered the habits and customs of the civilized world.

To no country was the time and circumstance of Watt's improvement so important as to our own. From that period until the twentieth century, Great Britain had been comparatively free from war. The great continental nations, on the other hand, had been frequently embroiled, and it was during the Napoleonic wars that we laid the foundation of an industrial supremacy that opened up to us the markets of the world. With some important natural resources, a unique geographical position, and vast colonial possessions, this country was able to take advantage of scientific discovery and mechanical invention, and retain for a considerable time the leading place in initiating a new period. The mechanical invention of a Glasgow instrument

maker nearly two hundred years ago was the chief technical key to this achievement.

In the engines which man uses to wrest from coal the stored-up energy of the prehistoric sun the line of progress of the last century has been to secure more power from each pound of fuel used. The steam-engine is a heat-engine. The coal in burning produces heat—each pound of coal giving about 14,000 units. This heat is taken to the engine in the form of hot steam, and when the steam passes out of the engine it is cooler. The useful portion of this cooling is due to the expansion of the steam in forcing the piston backwards and forwards, and the rest is more or less unavoidable loss. The higher the temperature of steam to begin with, and the lower its temperature at the end, the greater will be the amount of work done, provided that the losses do not increase in the same proportion. If therefore the greatest amount of heat is to be obtained from the coal, it is necessary to consider two sets of losses—those which occur in the boiler, and those which occur in the engine. Let us consider the boiler first.

THE MODERN BOILER

In the chief types of boiler in use a century ago the hot gases pass through a number of tubes or flues to the chimney. If these tubes are large in diameter, as in the Cornish or Lancashire boiler, the hot gases in the middle of the flue do not come into contact with the walls, and the heat they contain escapes with them up the chimney. To prevent this, wide flues have water tubes across them, which not only intercept the hot gases, but encourage more rapid circulation of the water. Return flues are built in the brickwork on either side of the boiler, and the Lancashire type is a very efficient form of steam generator for continuous operation. For intermittent working it is wasteful because of the mass of brickwork which has to be heated every time the boiler is required.

The efficiency of a boiler is measured by the quantity of water it will convert into steam per pound of fuel consumed. It must have a large heating surface, a fiercely burning fire, and be capable of withstanding high pressures. Increase in heating surface has been secured by arranging that a portion of the water is exposed to the fire in narrow, inclined tubes amongst which the hot gases flow on their way to the chimney. On account of their relatively small diameter—3 or 4 in.—they may be made of thin material and yet be strong enough to resist the high pressure to which they are subjected. The water in these tubes takes up heat rapidly, decreases in density, and rises through the upper ends into a cylinder or drum which contains the main body. Cool water then flows from the drum into the other ends of the narrow tubes and the circulation is kept up. In this way, not only is the water in the tubes heated

quickly, but it moves on quickly to make room for cooler water from the drum.

Very frequently boilers on land can be equipped with chimneys of such a height that the natural draught is sufficient to maintain rapid combustion, but forced draught is coming into greater use. The air for this purpose is usually supplied by a fan, which forces it directly into the furnace; but on ships the fan is placed outside the stokehold, which is closed up so that the men work under the pressure which drives the furnaces. The practice on locomotives, invented by George Stephenson, was to allow the exhaust steam to pass up the chimney, but this is far too wasteful to be used for stationary or marine engines under modern conditions. More especially, fresh water at sea is so scarce that every ounce passing through the engine is condensed, freed from oil, and returned to the boiler.

A saving is effected in large boiler installations by the use of 'economizers' which consist of nests of tubes, through which the feed-water passes, arranged between the boiler and the smoke-stack. A quantity of heat which would otherwise be lost is caught and returned to the boiler, which has less heat to supply than if the water was fed in cold.

The amount of steam at a given temperature that can be produced per pound of coal depends a good deal on careful stoking. If the fire is allowed to burn low, and is then choked with a heavy charge of coal, much smoke will be produced, the pressure of the steam will vary, and the boiler will be inefficient. Such irregularity is avoided in large installations by the use of mechanical stokers. The coal is fed into a hopper in front of the boiler and is carried into the furnace on a wide chain belt or pushed in by a ram which moves backwards and forwards. By this means a steady supply of fuel is provided without opening the doors and allowing a sudden inrush of cold air.

A further device, though this affects the efficiency of the engine rather than that of the boiler, may be mentioned here. In most boilers it is practically impossible to draw off dry steam, i.e. steam free from small drops of water; and this water serves no useful purpose in the production of power. The presence of water in the steam is known as 'priming' and has to be reduced as far as possible, either by a special device which removes the water, or by superheating steam by passing it through tubes contained in the flues on its way to the engine. It is possible to give it a temperature considerably higher—by 100° or 200° F. —than the temperature in the boiler. The tiny drops of water are converted into steam and its volume increases. The thread of steam in the hot tube is drawn out and lengthens towards the cylinder, which it fills with less weight than would be required at a lower temperature. Not only are the defects of priming eliminated, but the increase of temperature produces the same effect as an increase of pressure, and the engine

uses less steam per horse-power. Superheating is no new device, but contrivances for effecting it have improved a good deal in recent years, and metallic packing with non-carbonizing cylinder oils have rendered a higher degree of superheat possible. It is now applied to every type of engine—stationary, marine, and locomotive—and it may be said generally that a saving of 1 per cent of fuel is effected by every 10 degrees of superheat.

There are several very interesting methods of automatically regulating the supply of feed-water to a boiler. Under ordinary circumstances it is

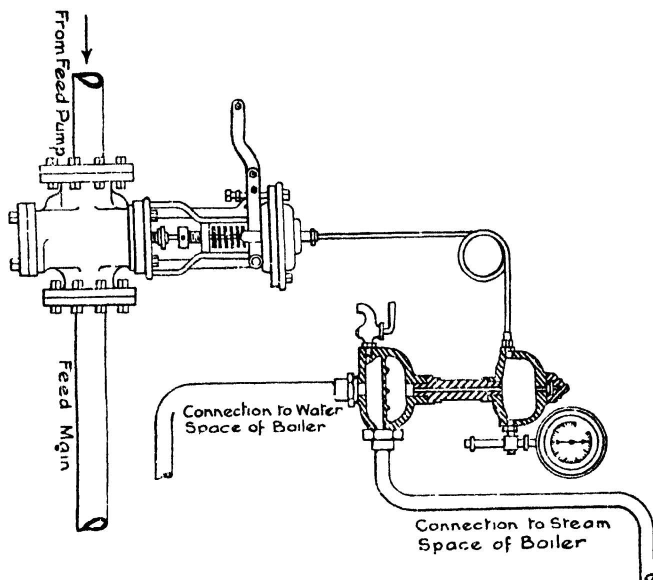
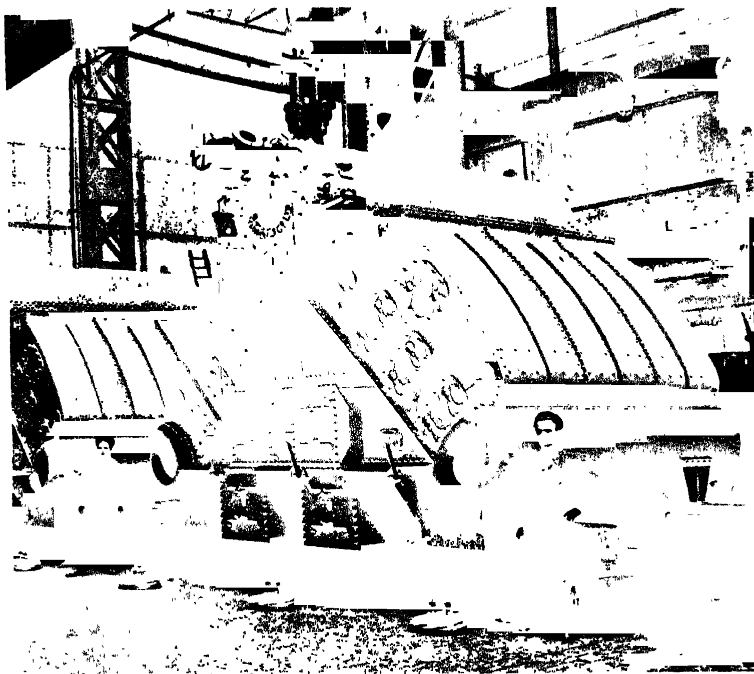
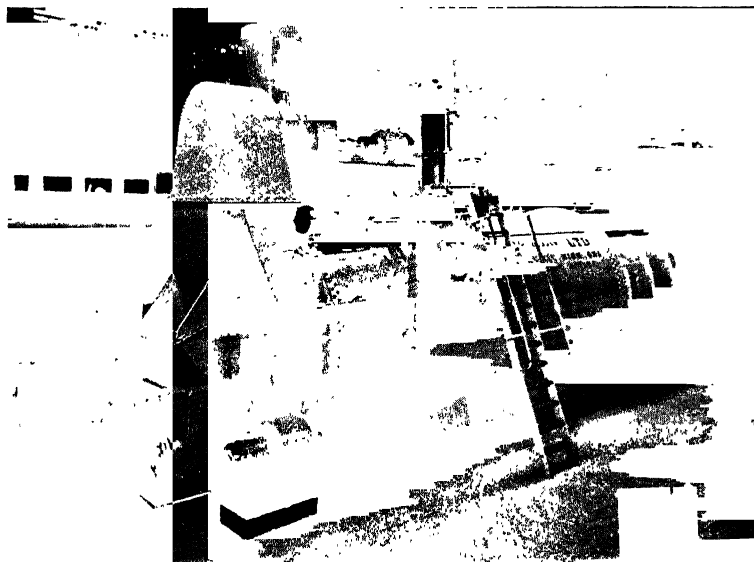


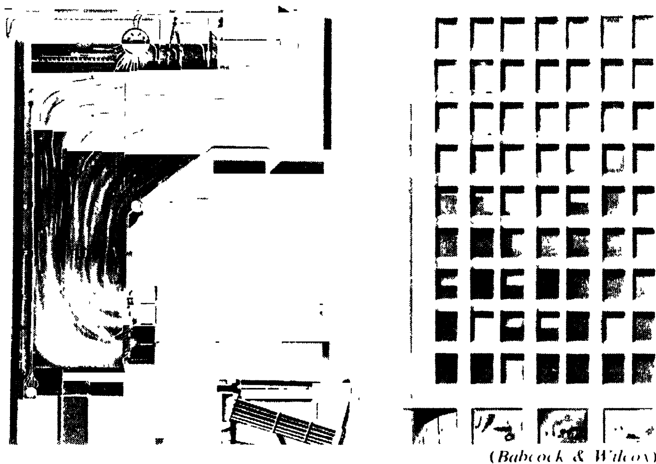
Figure 3. The Crosby feed-water regulator

the business of the man in charge to keep an eye on the water-gauge, and to adjust the supply from the feed-pump whenever necessary. There is one level which gives the best results in practice, and a constant level in any case leads to less priming, more uniform pressure, and generally to more regular working. If this can be taken out of the hands of a man and put under the control of a machine, so much the better. The particular form selected for illustration is that made by the Crosby Steam Gauge and Valve Company, which is shown diagrammatically in Fig. 3. The tube between the valve which admits the water from the pump to the boiler, and the bulb, which has a partition across the middle, are filled with distilled water. Any change of temperature in the lower half of the bulb, under the partition, will cause this water to expand or con-


(A. F. Yarrow)

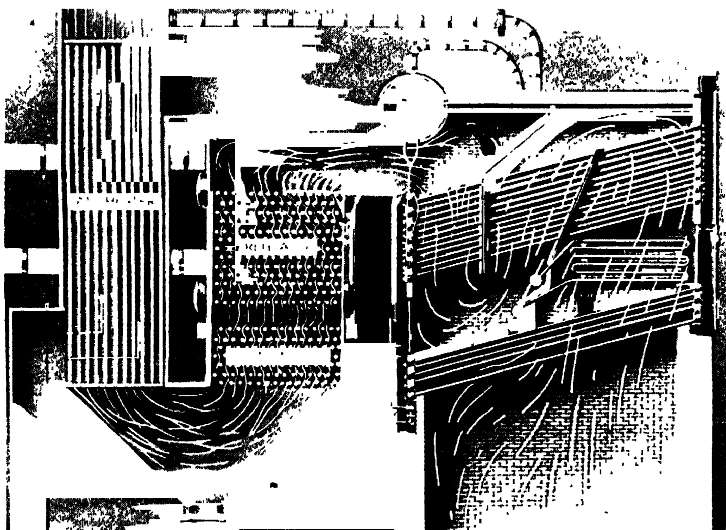
VIIa. The Yarrow boiler





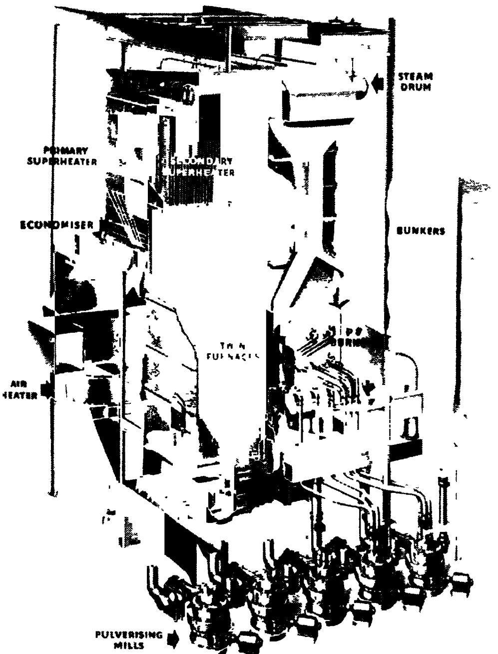
(Babcock & Wilcox)

VIIIa. Drawing of a modern boiler, an older type and a 10-storey office building to scale



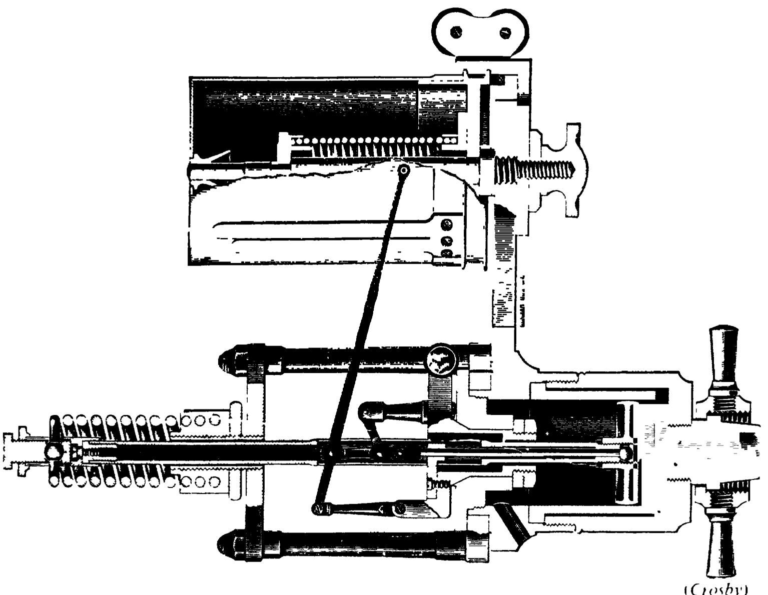
(Babcock & Wilcox)

VIIIb. Diagram of flow of gases through boiler tubes, superheater, reheater economiser and air heater



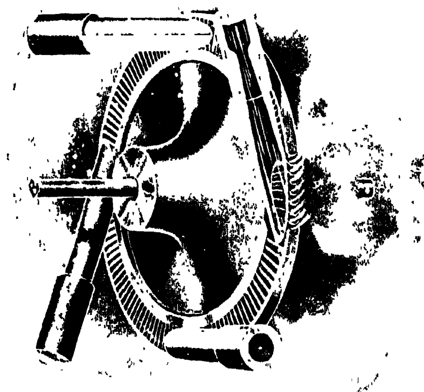
(Babcock & Wilcox)

xa. Perspective drawing of a Babcock and Wilcox twin furnace Radiant boiler capable of 830,000 lb. hr. units for Castle Donington. Note the size of the man (to scale) on the firing floor near to the burners



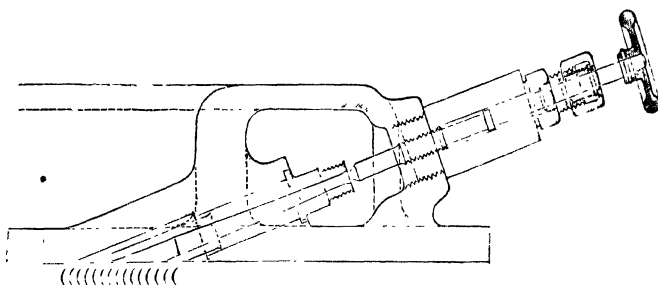
(Crosby)

ixb. Section of a steam-engine indicator

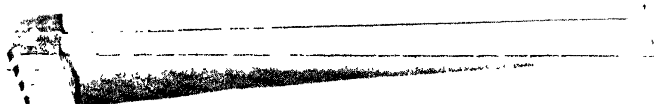


(Greenwood & Batley)

Xa. Disc and nozzles of an impulse turbine



Xb. Section of nozzle of impulse turbine



(Metropolitan-Vickers)

Xc. Final twisted and tapered low pressure blades

tract, and thus to open or close the valve. The bulb is fixed so that the partition is at the desired level of the water in the boiler, and the tubes connect the lower half with the steam space and the water space respectively. If the water-level in the boiler rises ever so little, then water from the lower part of the boiler comes into contact with the partition, cools it, and closes the valve. But if the water-level in the boiler sinks, steam enters the bulb, warms up the distilled water through the partition and opens the valve. It is difficult to imagine a more beautiful contrivance than this. When steam is being drawn from the boiler, the valve is rarely completely closed or open, but executes a slight movement according to the rate of evaporation. With unerring accuracy it feels the pulse of the boiler, and responds to the faintest variation of level. The machine does what no human being should have to do: by sheer concentration upon one mechanical detail it executes its duty with perfect reliability. It has no variety of initiative to be destroyed; and the man has.

One of the first successful types of water-tube boiler is the Babcock and Wilcox. It is still widely used for pressures up to about 350 lb. per sq. in., and for outputs of about 50,000 lb. of steam per hour. A section through the boiler shows very clearly the arrangement of inclined tubes fixed at right angles to the stream of hot gases, and connected at each end with the drum at the top. It also shows the baffle-plate by which the hot gases, having passed between the upper halves of the tubes, are directed in turn between the lower halves. The U-shaped tubes, fixed horizontally just below the drum, form the superheater. In front is shown the hopper into which the coal is fed, and below is the mechanical stoker mounted on a truck so that it can easily be withdrawn from the furnace. The coal falls from the hopper on to a chain belt, which passes round toothed rollers at each end of the carriage, and feeds the coal gradually on to the grate. The grate is fitted with rocking levers which, moving backwards and forwards, prevent the formation of clinker and keep the fire-bars clear of ashes.

The Yarrow boiler illustrated in Fig. 4 and Plate VII*a* is the outcome of many experiments made by A. F. Yarrow, the well-known engineer and shipbuilder, who did so much for the scientific development of shipbuilding and marine engineering. It consists of two lower drums and an upper drum, with which the lower drums are connected by tubes arranged on each side of the furnace. A superheater is fixed between the tubes and the casing on one side, and a feed-water heater in a similar position on the other. The feed-water enters the upper drum at the side and is deflected by a plate down the outer row of tubes to the lower drum, so that it does not mix immediately with the main body of hot water which is being converted into steam. The heat can be cut off from the feed-water heater or superheater by dampers on each side of the uptake leading to the chimney.

The Babcock and Wilcox boiler is made in two forms, one for land and the other for marine purposes; the Yarrow is made in only one form. They enable steam to be raised quickly and produced rapidly, and like all other boilers can be adapted to burn oil-fuel.

The development of steam generation has been very swift during the present century. In the old 'fire-tube', 'smoke-tube' or 'shell-type' boiler, of which the Lancashire is a still popular example, the hot gases from the furnace pass through tubes which are surrounded by water.

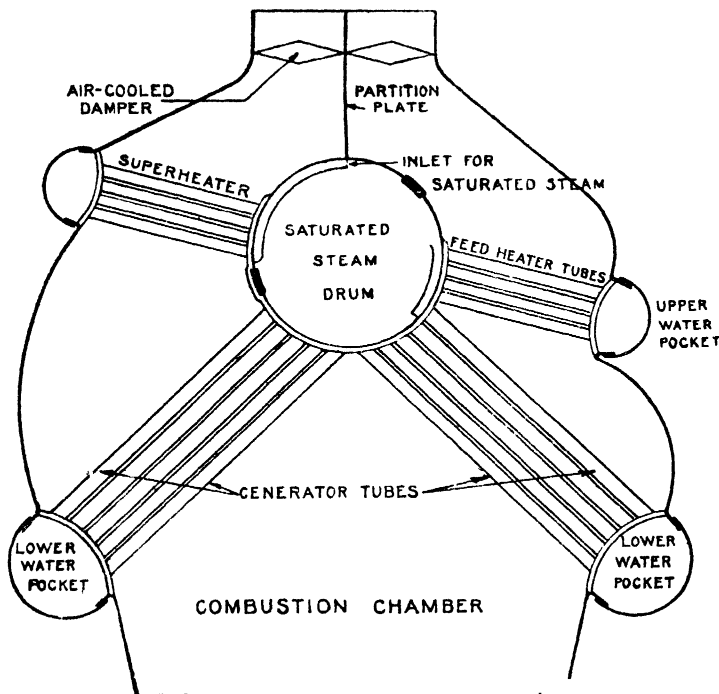


Figure 4. Section of Yarrow boiler

Another type of shell boiler still much used today is the 'Economic'. The flow of gases in it does not follow the same path as in the Lancashire, for instead of flowing down the two main flues and returning outside the boiler, between the steel and the brick setting (and making a final pass underneath), the gases go down one main flue and then turn back at the end, returning along a number of small-diameter tubes which go through the water, before going on to the chimney.

An example of this type of boiler is seen in Plate VII*b*.

In the 'Super-Economic' boiler there is a further set of tubes through which the gases pass for the third time before going up the chimney.

Up to pressures of 250 lb. per sq. in. and evaporation rates of 25,000 lb. of steam per hour, the shell boiler is usually preferred because of its lower first cost and general simplicity.

For working at higher pressures and bigger rates of steam-raising, the water-tube boiler is preferred. In this type of boiler, the water to be heated is inside the tubes, while the hot gases play on their outside. In the shell boiler the heat passes from the inside of tubes outwards into surrounding water; in the water-tube boiler, it passes from outside the tube into the water inside.

All the generation of steam takes place inside the tubes, through which water circulates. The tubes are connected at both ends to one or more drums. A constant water level is maintained in the drums, and the steam collects in the space above. Cool water is fed to the lowest and coolest parts of the tube system, and rises as it is heated, setting up a continuous circulation, and discharging a mixture of steam and water in the drum. The steam frees itself from the droplets of water, or is mechanically freed from them by steam separators, and is drawn off to pass through the superheater, and thence to the turbine or other machine utilizing it.

When the Lot's Road Power Station in London was built in 1908, it was equipped with no less than 64 boilers to provide steam for 8 turbines producing 40,000 kW. Today, one turbine fed with steam from one boiler, may produce 100,000 kW., which is twice as much. The comparison of size between such a boiler, with one of an older type, is shown in Plate VIII*a*. The huge modern boiler is as high as a ten-storey office building.

Very large 'Radiant' boilers, illustrated in Plate IX*a*, are being built for the Castle Donington Power Station of the British Electrical Authority, the first of which should be in operation in 1955. It will be 150 ft. high, only 25 ft. less than Nelson's Column in Trafalgar Square, and will contain 41·5 miles of pipes. This boiler will generate 830,000 lb. of steam per hour at a pressure of 1,600 lb. per sq. in. and a temperature of 1060° F. It has twin furnaces, and will consume $\frac{3}{4}$ ton of coal per minute. The steam-drum will be 50 ft. long, and 5 ft. 6 in. internal diameter. It will be made of steel $5\frac{1}{4}$ in. thick. Its weight will be 120 tons.

Up to generating rates of 250,000 lb. of steam per hour, travelling grate stokers or spreader stokers are used. The former consists of an endless chain which acts as the grate, and travels slowly through the furnace, coal being fed on to it at one end, and ash being removed at the other. In the latter type, coal is thrown on to the furnace evenly and continuously. At generating rates above 250,000 lb. per hour, and often for smaller boilers, pulverized fuel stokers are used. The coal is

first ground as fine as flour, and then blown by an air current through burners in the walls of the furnace, in which it is burned like a gas.

Oil is sometimes used for land boilers, as at the Bankside Power Station in London, and almost invariably in marine boilers. Natural gas, and gas from blast-furnaces, and coke ovens are also used when available in sufficient supply.

Working pressures of 1,600 lb. per sq. in. and temperatures of 1000° F. are now not unusual. Under these conditions the pipes carrying the steam to the turbine, and the first rows of turbine blades, run at a dull red heat.

The principle of steam-raising begins to change at these high temperatures. In general, heat is transferred from the furnace to the tubes by direct radiation, or by convection. In the latter case, the hot gases flow over the tubes and communicate their heat by contact. At the higher temperature, the communication of heat from the furnace to the water or steam depends more and more on direct radiation and less and less on convection. The amount of tube surface heated by convection is no more than is needed for constructional purposes. As nearly all the heating in a boiler such as that illustrated in Plate IX*a* is done by radiation, it is described as of 'Radiant' type. These boilers may be regarded as water-cooled furnaces, whose walls consist of bare tubes filled with water. The hot gases after passing over them are drawn to heat the tubes of the superheater. They may also pass over the tubes of a reheater. These are fitted to many of the big turbines described on p. 46. Steam which has done a certain amount of work in passing through several stages of the turbine is taken out of the machine and reheated, before passing to the next stage of the turbine. The principle of turbine feed heating has made one of the greatest contributions towards the higher thermal efficiency of generation of electrical power.

After the gases have passed through the furnace, superheater and reheater, they are drawn through an 'economizer' to heat the water being fed to the boiler, and through an 'air heater', to heat the air entering the furnace from the atmosphere for combustion. A diagram of the general arrangement of these various parts is given in Plate VIII*b*.

The efficiency of big steam generation plants has doubled in the first half of the present century, by increased scale, making the extraction of heat more complete, improving materials, and applying a deeper range of science to the problem of design.

THE RECIPROCATING ENGINE

Before considering the modern improvements in the steam engine it will be desirable to recall briefly how the engine works. Referring to Fig. 5 the steam enters the steam-chest, and when the crank is in the

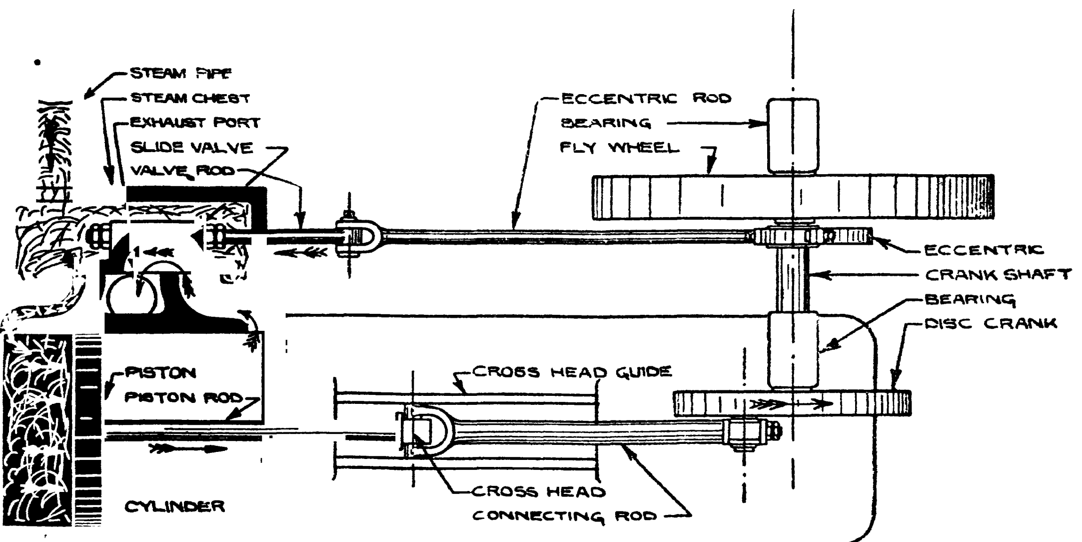


Figure 5. Section of a simple steam engine

position shown, it passes through the back port into the cylinder, and presses the piston forward. *Before* the piston has reached the end of its stroke, the valve moves so as to admit steam on the other side of the moving piston to steady it; then the back port is put into communication, through the hollow in the underside of the slide valve, with the exhaust port. The steam entering at the front of the piston now forces it back until, at the end of the stroke, it is allowed to escape through the exhaust. Since the time of Watt it has been the custom, in all engines in which a high efficiency is required, to condense the steam issuing from the exhaust, either by passing it through a nest of tubes conveying cold water (surface-condenser), or by leading it into a chamber containing a spray of cold water (jet-condenser). In either case an air pump is used to reduce the back pressure on the piston.

The object of admitting steam in front of the moving piston is to prevent shock, by forming a 'cushion' which reduces the speed of the piston gently. The object of cutting off steam early in the stroke is to utilize as much as possible of the heat energy in the steam. Expansion produces cooling, and the heat which disappears corresponds, when allowance has been made for that used in raising the temperature of the cylinder, to the work done on the piston. If the steam is cut off at one-third stroke, it expands to three times the volume admitted; if at a quarter stroke to four times; if at one-fifth to five times, and so on. The disadvantage of too great a range of expansion in an ordinary cylinder is that the condensation occurs upon the cylinder walls and thus is re-evaporated again. Generally the cylinder has a steam jacket to prevent condensation. Further, the steam has to pass out through the same ports by which it entered. Unless, therefore, the steam emerges with a very high velocity, congestion will occur in the ports if the ratio of expansion has been high, and an excessive back-pressure would be produced on the piston. An expansion of more than five or six has been found to be undesirable.

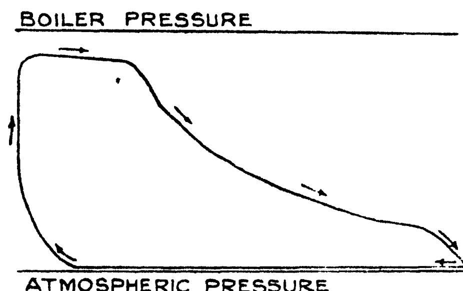


Figure 6. Indicator diagram

In order to see why expansive working is economical it is necessary to understand what is going on in the cylinder. Suppose a piston is fitted in a tube connected with one end of the cylinder, and held down by a spring which will allow it to move up or down as the pressure in the cylinder varies. If a pencil is fixed to this piston it will trace on a

paper held against it a line representing in length the difference of pressure which occurs during the stroke. Suppose next that the paper is mounted on a small drum which is connected to the crosshead (or, piston rod) of the engine by a string in such a way that it rotates as the piston moves. A fixed pencil pressed against this drum would trace a line on the paper representing the length of the stroke to scale, and the rate at which this line was drawn at any point would correspond to the speed of the piston at that stage of its journey. But if, instead of the fixed pencil, the pencil registering the changes of pressure were used the line traced on the paper would indicate both changes of pressure and the corresponding movement of the piston. Such an arrangement is called an indicator and the figure traced on the paper is called an indicator diagram (Fig. 6).

The shape of the diagram furnishes information as to the variation of pressure throughout the stroke, and the rapidity with which steam enters or leaves the cylinder. Its area represents to scale the work done by the stream. The problem of the engineer, therefore, is so to adjust the initial pressure, cut-off, and movements of the valves as to obtain a maximum area for a given weight of steam. In Fig. 5, the cut-off is at quarter stroke. Remembering that the boiler pressure and the stroke are fixed, it will be seen that if there was no cut-off—if steam was admitted at full pressure to the end of the stroke—the area of the diagram and, therefore, the work done would not be twice as much though four times the weight of steam would have been used.

Many of the improvements in the first hundred years were improvements in valves, and in the methods by which they were operated. Friction was reduced, steam was admitted more quickly and allowed to escape more quickly, and the point of cut-off could be varied to meet different conditions of working. The old D-shaped slide valve (Fig. 5) is difficult to keep steam-tight without unduly increasing the friction, and has been replaced in marine engines and high speed engines for electric power stations by the piston valve. In this case the valve chamber is like another cylinder, to which steam is admitted first, and the movement of two pistons on one rod open and close the ports between the two. Again the desirability of opening and closing the ports quickly has been met by the use of drop valves and valves of the Corliss type.

A very interesting type now being made is the Uniflow engine. This has a very thick piston, the thickness being nearly half the length of the stroke. The exhaust ports are situated in the middle of the cylinder and are put into communication with each and alternately by the movement of the piston. This avoids the reversal of flow which ordinarily occurs when the steam, having forced the piston to the end of its stroke, escapes through the same opening by which it entered.

The problem of obtaining a large amount of work depends upon

higher initial pressure and lower pressure of exhaust, or in other words upon the range of expansion. There are, however, several disadvantages in expanding steam to more than five times its original volume in one cylinder; so the compound triple expansion and quadruple expansion engines were devised in which the steam passes successively through two, three, or four cylinders of increasing size to accommodate its increased volume.

The use of a condenser to reduce the back-pressure was Watt's greatest gift to the steam engine. The increase of efficiency by expanding the steam and condensing it in a vacuum is so great that it justifies the use of air-pumps to remove the exhaust steam from the engine, and water-pumps to circulate the cooling water.

While the various improvements which have been described have been adopted in both locomotive and marine engines, these have retained to a large extent their original form. With stationary engines, however, there is a marked tendency to replace the horizontal by the vertical type and to employ high speeds. The later necessitates reliable material and unimpeachable workmanship. But it also introduces certain mechanical difficulties which require special means to overcome them. The first of these is lubrication. When two surfaces are rubbing together they soon become hot, unless they are separated by a film of oil. With high speed engines very large forces are called into play, and a thin oil would be squeezed out. Again, at high speeds, the film is liable to be broken and cavities formed. Both these dangers are avoided by forcing the oil between the surfaces by a small pump driven from the engine shaft.

The next problem is that of vibration. As the piston moves backwards and forwards, it alternately pushes and pulls the crank. This produces alternating pushes and pulls in the frame or foundation which connects the bearings with the cylinders, and when these alternations are taking place 600 or 700 times a minute a good deal of vibration may be produced.

But a more serious vibration may arise from another cause. The weights of the rotating parts are not equally distributed round the shaft. The crank-pin and connecting-rod are moving round the shaft—now in front, now beyond, now above, now below. If a stone is whirled round at the end of a string the latter is stretched tightly, and if the stone is heavy or is whirled round very rapidly the string will break. The force exerted outwards by a rotating body is given by the formula:

$$\frac{WV^2}{gr}$$

where W is the weight, r is the radius of swing, V is the velocity in feet per second, and g is the gravitation constant (= 32·2). Suppose

the weight to be 100 lb., the radius 20 in., and the number of revolutions per minute 300, the force on the bearings due to the rotating parts would be nearly two tons. This may squeeze out the lubricants, cause over-heating, and even burst the bearings. In order to avoid this, the sides or slabs of the crank are continued backwards and expanded in the shape of a fan in such a way as to balance as nearly as possible the rotating parts on the other side of the shaft. In this way an approximate solution can be found. With two cranks at right angles the problem is more difficult. In the locomotive the reader will have observed that the space between two spokes of the driving wheel is filled in. These solid masses of metal prevent in some measure the excessive vibrations that are liable to occur at high speeds.

While many horizontal engines are still made, the type *par excellence* of modern reciprocating engine is a high-speed, totally enclosed vertical engine with forced lubrication. A vertical engine has a great advantage over a horizontal engine of the same power in the matter of space. Again, the vertical position results in more even wear of the cylinder liner and stuffing boxes. High speed gives the steadiest running, total enclosure keeps out dust and grit, and oil fed into the bearings and over other rubbing surfaces under pressure from a small pump renders the engine practically fool-proof.

Much has been written of the marvellous reliability of a modern watch, but when it is stated that a Bellis and Morcom compound vertical engine installed in a chemical works ran for 99·77 per cent of the total number of hours in a year, making 85,000,000 revolutions in five months without a stop, and required no repairs or adjustments, some idea will be gained of the accuracy of workmanship, durability of material, and reliability of a modern steam-engine.

THE STEAM TURBINE

The type of engine which has been described has both advantages and disadvantages. It is as efficient as a steam-engine can be over a wide range of load, and it is capable of being readily adjusted to special conditions. It is the concentrated essence of more than a century of invention directed to the attainment of efficiency without modifying the principle of action. But in large engines there are heavy masses of metal in the piston, piston-rod, cross-head, and connecting-rod, which move at high speeds and have their direction reversed many times a minute. Part of the energy of the steam is used in setting these in motion, and part in bringing them to rest preparatory to setting them in motion again in the opposite direction. In fact, a reciprocating engine is wasteful in starting and stopping a portion of its own moving mass. Moreover, the effect of the connecting-rod on the crank varies

throughout the stroke, reaching a maximum only when the two are at right angles. Consequently engineers have endeavoured, from the beginning, to obtain a direct rotary force upon the shaft, without the intervention of piston, connecting-rod, or crank. The result of their efforts is represented by the steam turbine.

The simplest form is that invented by Gustaf de Laval, and its action is explained by Plate X*a*. The disc has a number of curved vanes fitted radially near its outer edge, and overlapping like the laths of a venetian blind. The steam is directed upon these by four, six or more nozzles, one of which is shown transparent in the figure, in such a way that it impinges upon the blades and causes the wheel to spin round. The whole arrangement is enclosed in a case through which the shaft passes, so that the steam can be drawn off after it has gone through the wheel and either discharged into the air or condensed.

There are several scientific principles of great interest involved. The first of these determines the shape of the nozzles, one of which is shown in section in Plate X*b*. It will be observed that the size of the opening increases as the mouth is approached. If steam is allowed to escape from a narrow opening into a region of much lower pressure, it is 'throttled', and has only a moderately high velocity. If, however, the opening expands towards the mouth the steam expands, and acquires a very high velocity; hence though the weight of steam may be very small it is able to exert considerable force upon anything which stands in its path. Each blade therefore receives an impulse from the jet of steam which issues from the nozzles with a velocity of 3,000 or 4,000 ft. per second.

If the wheel be prevented from rotating the steam will issue on the other side of the wheel with the same velocity that it left the nozzle, but this velocity will be in another direction—the direction in which the paths between the vanes point on the exhaust side of the wheel. Suppose the wheel to be rotating so that the vanes are moving as fast as the steam is issuing from the nozzle, the steam then will exert no force upon them at all. It should be clear therefore that there is some velocity between nothing and the velocity at which the steam is issuing at which the greatest amount of useful work will be done, and this is nearly half the velocity of the issuing steam.[1]

The velocity of steam expanding through a nozzle of the type shown is very high, and may easily reach 3,000 or 4,000 ft. a second. This means that the vanes ought to move at 1,500 to 2,000 ft. per second, or 90,000 to 120,000 ft. per minute! In the case of a small machine with a wheel only 6 inches in diameter this would involve, theoretically, a speed of nearly 80,000 revolutions per minute. In actual practice the speed ranges from 30,000 r.p.m. in the small turbines to 9,000 r.p.m.

[1] Compare the Pelton wheel, p. 5, which is an 'impulse' water turbine.

in the larger ones. Such an enormous velocity cannot be applied directly to any machine, and the power has to be transmitted through toothed gearing.

From what has been said about vibration and balancing on p. 40, it will be clear that the turbine brings into play a series of problems from which the reciprocating engine is relatively free. The centrifugal forces in the wheel cause large stresses which tend to burst it, and the best possible material must be used. Moreover, no amount of care will result in an accuracy of workmanship that gives perfect balance, and the tiniest fraction becomes serious at these high speeds. Some compensation has, therefore, to be sought which will render such small inaccuracies as are unavoidable free from danger; and this has been found in an interesting property of rotating shafts. If a thin spindle is rotated at a gradually increasing speed it begins to bend and whirl instead of rotating in a straight line. This is most marked at one particular speed, which depends upon the length and stiffness of the shaft. At higher speeds than this the shaft stops whirling and settles down to steady motion, just as a top 'goes to sleep' at high speed. It will be observed that in Plate X*a* the wheel is mounted on a slender shaft, and this is of such dimensions—only $\frac{1}{4}$ in. diameter for 5 h.p., and only $1\frac{1}{4}$ in. diameter for 300 h.p.—that the 'critical speed' at which the greatest whirling takes place is below that at which the turbine is designed to run. The case surrounding the wheel allows for a little play so that the turbine can be run up to its steady condition without the blades being torn off.

While de Laval's turbine has been described first on the ground of its simplicity, it was later in point of time than the one which is now to be considered. Charles Parsons filed his first patent for a reaction turbine in 1884, and in 1885 a machine was constructed which, though rotating at 18,000 r.p.m., gave great satisfaction. In its modern form it consists of a drum upon the outer surface of which are fixed circular rows or rings of blades, and the casing in which the drum is enclosed also carries rings of blades, projecting inwards, which fit with very small clearance between successive rings on the drum. The shape of the blades and their appearance on the drum are shown in Plate XII*a*. Steam enters the first ring of fixed blades and is directed by them upon the first ring of moving blades at a proper angle. The drum is not parallel, and successive rings of blades increase in diameter from the high pressure to the low pressure end, where the steam leaves. The steam, therefore, passes through a larger and larger space, and the expansion takes place as it goes between the blades. The practical consequence of this is that the expansion is split up into a number of stages and the reaction turbine rotates at a lower speed than the original impulse turbine.

From these two fundamental types several forms have been evolved.

The Rateau turbine, for example, is an impulse turbine with a number of discs on the same shaft, but running in separate chambers through which the steam passes in turn. By this plan the velocity is split up into a series of stages. Some turbines partake of the character of both types, they have a disc and a drum. Superheated steam acts on the disc and is then expanded through fixed and moving blades of the Parsons type.

The words impulse and reaction are borrowed by analogy from the theory of water turbines, and the simple explanation which has been given is not very satisfactory. We shall, therefore, inquire a little more closely into the theory, and a very elementary knowledge of mechanics will enable the reasoning to be followed. The reader should, however, keep in mind Newton's three laws of motion, which may be stated as follows:

1. Force is that which changes or tends to change a body's state of rest or uniform motion in a straight line.
2. Change of motion is proportional to the impressed force.
3. To every action there is an equal and opposite reaction.

Suppose a jet of steam C impinges upon a blade AB as in Fig. 7. If the blade is smooth, friction may be neglected, the water will not change its direction. If the blade is fixed the new direction will be that indicated in the Figure, and since force is required to effect this, there will be a tendency for the blade to move in the direction of the arrow. If the blade moves, the steam will follow it up and this motion in the direction of the arrow will reduce the speed which the steam would have *towards the right* if the blade were fixed.

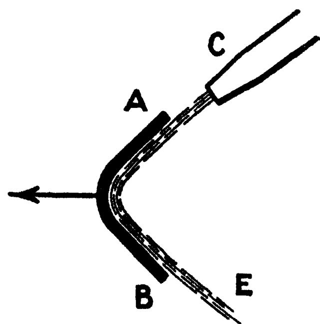


Figure 7. Diagram to explain impulse turbine

Now the quantity of motion or 'momentum' in a body is expressed by the product M × V, where M is the mass and V is the velocity of the body, and it represents a force. If M is in pounds weight and V in ft. per second, the force is given in poundals and must be divided by 32·2 (the constant of gravitation) to bring it to pounds. So that if M lb. of steam flowing over the blade has its velocity *to the right* reduced from V_1 to V_2, the force exerted on the blade must be the difference of the momentum before and after the change, or

$$F = \frac{MV_1}{32{\cdot}2} - \frac{MV_2}{32{\cdot}2} = \frac{M(V_1 - V_2)}{32{\cdot}2}$$

This is the principle of the impulse turbine. It must be noted (1) that

there is no change in pressure during the whole time that the steam impinges on the blade, (2) if the blade is fixed there is a change in direction only, and (3) if the blade is moving there is a change in *both* the magnitude and direction of the velocity.

Consider next the reaction turbine. Suppose the vessel A, Fig. 8, suspended so that it can swing freely, is filled with steam at 200 lb. per sq. in. Since gases exert pressure equally in all directions the pressure will be 200 lb. per sq. in. all over the interior of the vessel. But if it escapes at the nozzle there will be a force tending to make the vessel swing backwards in accordance with Newton's Third Law. This force

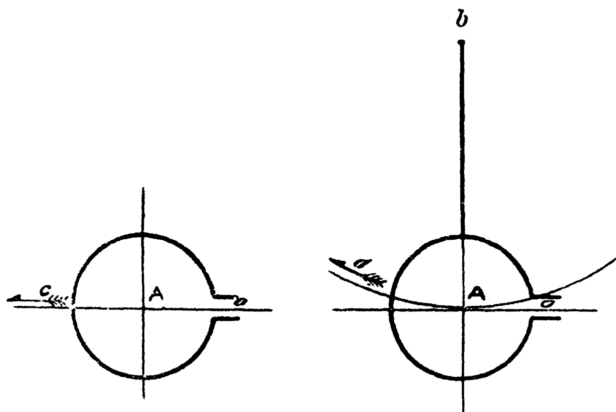


Figure 8. Diagram to explain reaction

depends upon the shape of the nozzle. If the sides are parallel, the outward pressure is never more than 0·58 of the inside pressure, or in this case 116 lb. per sq. in. The pressure tending to drive the vessel backward would then be 200 – 116 lb. = 84 lb. per sq. in. An expanding nozzle reduces the outward pressure, so that if it is properly designed the backward thrust may become 185 lb. per sq. in.—the difference between 200 lb. and the pressure of the atmosphere.

If now in Fig. 9 CE represent the fixed and AB, EF the moving blades of a reaction turbine, the change in the direction of motion of the steam will tend to force the moving blades backwards, and as these blades move the steam will tend to follow them up so far as the action is the same as the impulse turbine. But the shape of the blades is such that the pressure at B is less than at A, and the speed of the steam over the surface of the blades increases. This difference of pressure causes the blades to move backwards, just as in the case of the suspended vessel in Fig. 8. In a reaction turbine, (1) the steam falls in pressure and therefore expands as it passes through the moving blades; (2) the

work done in consequence of the change of momentum which the steam undergoes (*a*) by change of magnitude and direction of its velocity, in impinging upon and following up the blade, and (*b*) by the change of velocity as a result of expansion within the vanes. As a change of pressure occurs the reaction turbine is often called a 'pressure' turbine. Finally it may be noted that expansion takes place in both fixed and moving blades of a pressure turbine, and in the fixed blades only of a velocity turbine.

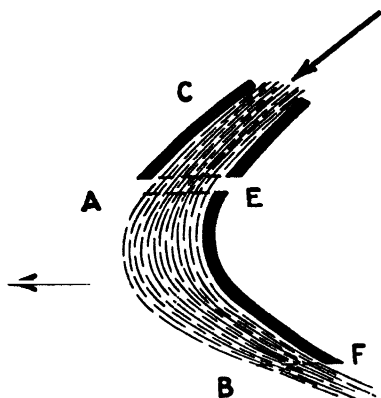


Figure 9. Diagram to explain principle of the reaction turbine

Though invented nearly forty years ago, the turbine was slow in development. The high speed of the de Laval type was a disadvantage for many purposes, and it was long before silent and efficient gearing, capable of transmitting large powers, was developed. The first Parsons turbine was of only 6 h.p. and until 1888 the largest was only 150. Then for six years the validity of the patents was in question and progress was hampered. But by 1908 machines of 10,000 h.p. were at work, while the steam consumption had been reduced from 20 lb. per h.p. per hour to 9 lb.

Today, Parsons steam turbines of 208,000 kW. or about 250,000 h.p. are in service.

STEAM TURBO-GENERATORS

Many of the largest steam turbo-generators now made combine the impulse and reaction principles, and thus gain some of the advantages of both types. The Metropolitan-Vickers Electrical Co. Ltd. has specialized in this field. It has already installed plants of an aggregate generating capacity of more than 14,000,000 kW. Such a firm, which engages also in making the condensers, feed heating and evaporating equipment, and the electrical generators, transformers and switchgear, is able to formulate and carry out complete schemes for big power stations.

The biggest steam turbo-alternator made by this firm is the 105,000 kW. machine installed in Battersea 'A' Power Station (Plate XI*a*).

In the multistage impulse turbine, the steam expands through a series of nozzles. After passing through a nozzle, part of the energy of the steam, represented by pressure and temperature, is changed into kinetic

energy, and the steam moves faster. Some of its energy of movement is then absorbed by turbine blades on which it impinges. As all of the expansion of the steam occurs in the nozzles, while the turbine blades revolve in chambers, in which the steam is at constant pressure, there is no tendency for the steam to leak around the ends of the blades, as in a reaction turbine, where the expansion occurs equally in the nozzles and in the moving blades. Theoretically, the reaction turbine is slightly more efficient than the impulse turbine, but this advantage is lost in the leakage around its blade tips, which cannot be avoided in practice. This is particularly so at very high steam pressures, where the blades are shorter, and the effect of a leakage will be greater in proportion to the size of the blade. On the other hand, at low pressures, with large and long blades, the amount of leakage around the ends is relatively much smaller. Hence in the Metrovick turbines, impulse stages are used at the high-pressure end, while towards the low-pressure exhaust end an increasing amount of reaction is used, for with the longer blades liberal clearances can be used without relatively large leakages round the ends.

The number of stages used in a turbine depends on considerations of thermodynamic efficiency and cost. The efficiency generally increases with the number of expansion stages and blade velocity, and is indicated for the same type of turbine by the formula Nd^2n^2, where N is the number of stages, d the mean diameter of the blading, and n the speed of rotation.

The improvement of the strength of the steel used in the disc and blades has enabled the diameter of turbines to be increased for the same speed. This allowed the production of the same degree of efficiency for a smaller number of stages. This makes the turbine shorter and reduces costs of construction.

It has been found that it is advantageous to divide the turbine into two or more sections, each in its separate cylinder, when inlet steam at very high temperature and pressure is used. By having two or more rotors, each rotor is smaller, and is subject to a smaller range of pressure and temperature.

Consequently, the amount of the turbine subject to the very high initial temperature and pressure is greatly reduced. Much less material is exposed to extreme conditions, and the high-pressure joints, which have to be kept in good condition, are smaller in area and subject to much less variation of temperature and pressure. Experience has shown that, in consequence, maintenance is much reduced.

Thermal efficiency is increased by raising the initial temperature and pressure, especially the temperature. This provides an increase in the available energy in the steam, and permits the utilization of a larger fraction of it. Also, the proportion of wetness in the low-pressure stages of the turbine is reduced.

The present limits to temperature are set by metallurgical considerations. Each improvement in the production of heat-resisting steels and alloys allows the initial temperature to be increased, and steady progress has been made by the metallurgists.

The raising of pressure without a corresponding increase of temperature is not so advantageous. It makes the construction more expensive, increases the power absorbed by the boiler feed pump, and causes excessive wetness of the steam in the later exhaust stages, which leads to corrosion of the blades.

Temperature and pressure are therefore raised together in such a way as to leave a final wetness of not more than 13 per cent–14 per cent in the exhaust steam. At 600 lb. per sq. in. the optimum temperature is about 850° F., at 900 lb. per sq. in. 900° F., and at 1,500 lb. per sq. in. 1,050° F.

The 105,000 kW. set at Battersea Power Station operates at a pressure of 570 lb. per sq. in. and a temperature of 800° F. Its speed is 1,500 r.p.m.

A two-axis 100,000 kW. unit at Battersea 'B' operates at 1,350 lb. per sq. in. and 950° F. in the initial cylinder. This produces 16,000 kW., and runs at 3,000 r.p.m. It discharges into a two-cylinder condensing set, running at 1,500 r.p.m., and developing the other 84,000 kW.

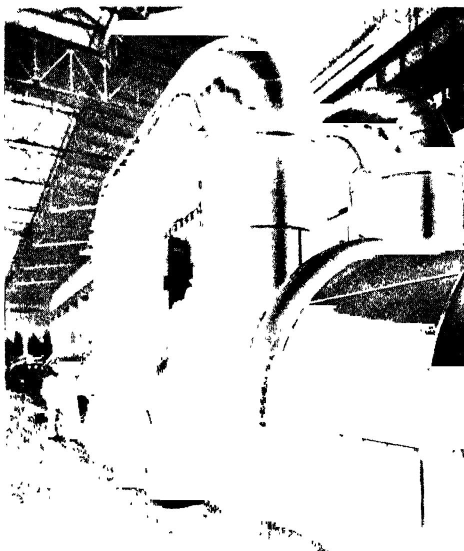
Two-cylinder units of 100,000 kW. are under construction for the Castle Donington station of the British Electricity Authority. These will operate at inlet conditions of 1,500 lb. per sq. in. pressure and 1,050° F. temperature.

At the Brimsdown station a 54,000 kW. unit operates at the high inlet pressure of 1,900 lb. and a temperature of 930° F.

When the pressure and temperature of the steam are very high, the casing for the rotor is made of forged molybdenum steel. Otherwise, it is generally made of welded steel. It is divided along the horizontal centre line, and is so accurately finished that the two halves can be bolted together without the use of jointing material to resist the very high pressure.

The tightening of large flange bolts holding the two halves of casings together is done by means of heat. After the nut has been tightened by hand, heat is applied in a hole drilled along the axis of the bolt. This makes the bolt expand, and lift its face off the flange. The nut is then turned through a definite angle by hand. As the bolt cools, it contracts and clasps the flange with the desired pressure. When the turbine is put into service, both bolt and flange expand together, so that the tension is permanently maintained.

The fixed diaphragms between the stages contain the nozzles through which the steam expands. The diaphragms are attached in halves, the top half to the inside of the top half of the casing, and the bottom half to the lower half of the casing.



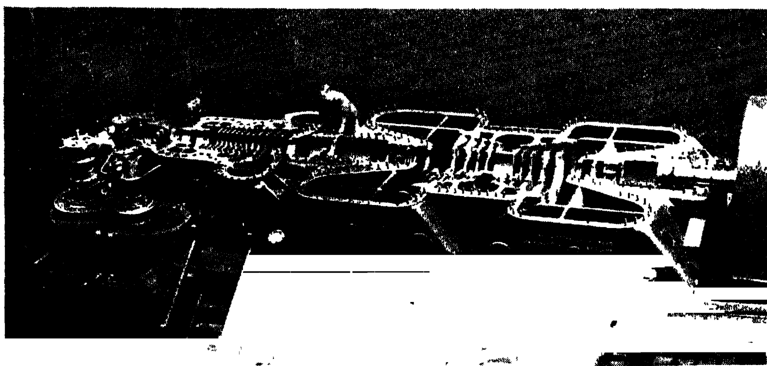
(*Metropolitan-Vickers*)

XI*a*. The 105,000 kW. 'Metrovick' turbo-alternator in Battersea 'A' Power Station



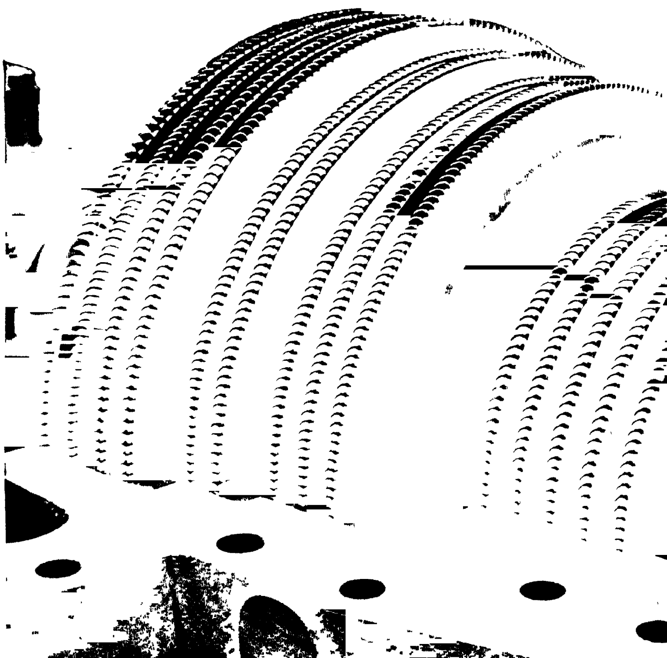
(*Metropolitan-Vickers*)

XI*b*. Assembly of long multifork blades, on low pressure disc



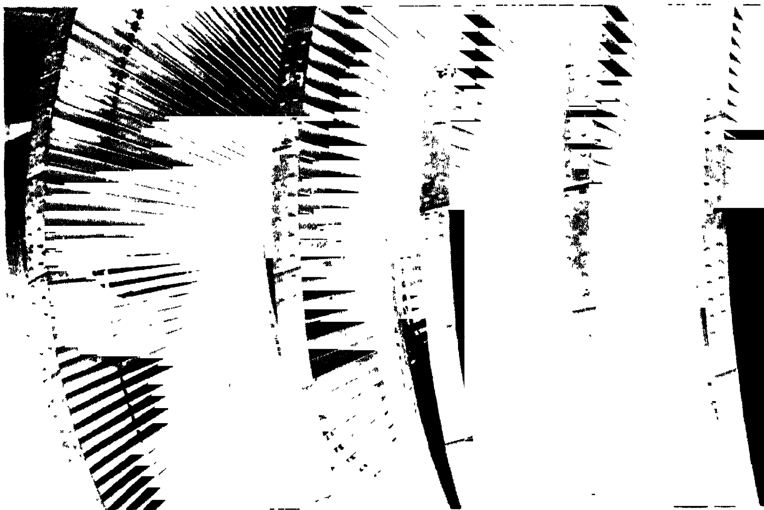
(*Metropolitan-Vickers*)

XI*c*. Bottom half of cylinder casings: 33,000 kW. turbine of the Electricity Supply Commission, South Africa



(*Brush*)

XII*a*. The completed rotor of a reaction turbine



(*Metropolitan-Vickers*)

XII*b*. Exhaust end blading of a 41,000 kW. turbine, after 78,000 running hours

In the high temperature and pressure cylinders, the diaphragms are built up of molybdenum steel plate. The nozzles are accurately machined out of molybdenum steel, and carefully fitted and riveted to the plate.

The low-pressure diaphragms are made of cast iron, with cast-in nozzles of rustless iron. The shafts are made of high-quality carbon steel, turned with increasing thickness towards the middle for the reception of the discs, which are pressed on hydraulically. But wherever possible, the discs are made solid with the shaft, being turned out of one solid forging.

The moving blades on the rotors are fixed in a variety of ways. Those on the high temperature and pressure discs are rolled out of stainless steel and other alloys. The sections as finally rolled are strictly accurate in shape, and possess a highly-finished surface which offers the maximum resistance to erosion. Each blade is held by two carefully fitted rivets, the heads of which are finished off by spinning, so that there is no heating or hammering to set up stresses.

In the final low-pressure stages, the blades are twisted and tapered. This enhances the strength of the blade, and of its roots. It also compensates for varying peripheral speed over the blade length, thus giving maximum efficiency. The twisted formation is obtained by the method of machining (Plate XI*c*).

Care is taken to ensure that the critical speed of the turbine is widely different from the running speed, and that the natural frequencies of the blades do not coincide with those of any running parts of the machine.

The prevention of the escape of the steam around the shaft presents an important problem. It is solved by a system of labyrinth glands, by which the steam is forced to follow a tortuous path through the maximum number of labyrinthine passages in a short distance.

Adequate drainage of the moisture produced in the low-pressure stages reduces the amount of moisture-erosion. In Metrovick turbines, this is achieved by placing annular channels around the diaphragms opposite the leading edges of the moving blades. The centrifugal force of the rotating blades throws much of the moisture into these channels, from whence it can be collected.

Plate XII*b* shows an untouched photograph of the exhaust-end blading of a 41,000 kW. turbine, which has been protected by this arrangement, after 78,000 hours' running. It is virtually free of erosion.

Metrovick turbines are fitted with thrust blocks of the Michell type (see p. 313).

The governor for regulating the inlet of steam according to the load consists of a horizontal shaft bearing two weights held by a spring. As the speed of rotation increases, the weights tend to fly apart, and begin to press a lever. This lever controls the flow of oil, under pressure,

into a piston. The rod of the piston, thus operated under considerable power, is attached to the main steam valves.

Thus the inlet steam is controlled by an oil relay system. A primary auxiliary oil relay valve is moved by the governor arm, and controls the movement of a relay valve. This in turn regulates the admission of oil to a power piston that controls the steam admission valves.

The oil relay system acts as a device for magnifying force, and enables the governor arm to operate under small variations of force, providing a very sensitive automatic governing of the turbine, in relation to changes in the load put on it.

The governor valves have streamlined passages, which enable steam to flow through them at high velocity with the minimum of loss.

An emergency governor of a ring type is provided. This consists of a ring, the centre of gravity of which does not coincide with the centre of rotation. As the ring goes round with the shaft its eccentricity of motion is increased by the centrifugal force developed in it. If the shaft rotates above a certain speed the eccentricity becomes so great that it leads to the operation of a trip-mechanism, which sets the oil relay system working and shuts off the steam.

The application of regenerative feed water heating is one of the most important features contributing to high thermal efficiency in large turbines. In this, steam which has already performed useful work is diverted from appropriate stages in the turbine, and is returned with the final condensed steam, or condensate, to the boilers. The diverted steam is thereby enabled to return its latent heat for heating feed water. Otherwise, the latent heat of the whole of the steam is lost when it is condensed into water in the condenser.

As the temperature and pressure conditions get higher and higher, the mass of the rotor becomes smaller and smaller in relation to the strong, heavy containing cylinder. Consequently, the light rotor is more liable to distortions and expansions than the heavy cylinder. Thus the distortions and expansions of one tend to be out of step with the other. Delicate electrical instruments are therefore provided to keep watch on these expansions and distortions.

The production of large turbines operating at high temperatures and pressures requires continuous research and testing. Faults in these big and expensive machines, working under such high conditions, can lead to very serious consequences. Hence every effort must be made to ensure perfection of design, materials, and workmanship.

Each disc of the rotors is subjected to magnetic and other tests in order to determine its soundness. Magnetic search coils are used, by which irregularities up to five inches below the surface of steel may be detected.

The blades are thoroughly tested in order to determine their fatigue

behaviour under long-continued stresses. Their natural vibration frequencies are determined so that they can be prevented from resonating with other vibrations and impulses. They are carefully examined in order to ensure complete freedom from cracks and other irregularities.

The resistance of blades, and their material, to corrosion is investigated under standing conditions, and under extreme conditions of temperature and wetness.

The investigation of the phenomena of creep, in which metals continuously change in size under stress at high temperature, is particularly important. The development of turbines working at higher and higher temperatures, thus giving higher and higher efficiencies, depends largely on the production of new steels and alloys which have higher resistance to creep.

The design of blades and nozzles is a subject of continuous experimental research. New designs are first tested by themselves in special set-ups, and then under working conditions in turbines.

Though the turbine can be used for any purposes, it is particularly valuable for driving electric generators and for the propulsion of ships. In the former case its high speed and uniformity of running are its main recommendations. With high speeds, high voltages can be secured from a generator of relatively small dimensions, while the turbine itself takes up less space than a reciprocating engine of the same power. For marine propulsion its advantages are reduction in weight, space, first cost and upkeep, high efficiency, and the fact that the condensed steam is not contaminated with oil, so that it can be returned to the boilers with less trouble in cleaning. The absence of parts gives a free exit to the steam and the back-pressure is reduced with less work from the pumps.

IV

INTERNAL COMBUSTION ENGINES

THE source of power in any heat-engine is the fuel. The greater the amount of heat produced by the fuel that is used in the engine, and the less that is allowed to escape from it, the more efficient does the engine become. In the ordinary steam-engine the heat produced by the burning coal is very largely wasted. Some of it goes up the chimney, some of it is radiated from the large surface of the boiler and steam pipes. It is clear that if the fire could be made to burn *inside* the cylinder, less heat would be able to get away until it had done the work required of it. But there is another advantage. No solid or liquid fuel burns so readily and so completely as a gas, which can be intimately mixed with exactly the amount of air required for its combustion. So what inventors have aimed at is to produce an engine in which the heat shall be liberated inside the cylinder and in which the combustion is as regular and perfect as can be.

A skeleton diagram of a gas-engine is given in Fig. 10. Suppose the piston is in the position shown in top figure. As it moves outward the valve G opens and admits gas, while the valve A opens and admits air. In this way the cylinder is filled with the mixed gases, and if the valves have been properly designed this mixture will be that which gives the best results on combustion. The next stroke of the piston compresses the mixture. As it reaches the end and is about to return, the charge is ignited by means to be described later, and the explosion forces the piston outwards. When it returns the exhaust valve opens and the products of combustion are swept out of the cylinder.

This series of operations is repeated every two revolutions of the crank, and is called the Otto Cycle. The engine is only single-acting—the piston is pushed towards the crank, and, as the flywheel turns, the crank pushes the piston back again in a sort of 'you push me and I'll push you' spirit. But the crank gives two pushes and one pull to the piston's one push, so that for one-quarter of the time the piston drives the crank, and for three-quarters of the time the crank drives the piston. If there were no flywheel the crank-shaft would move very rapidly for

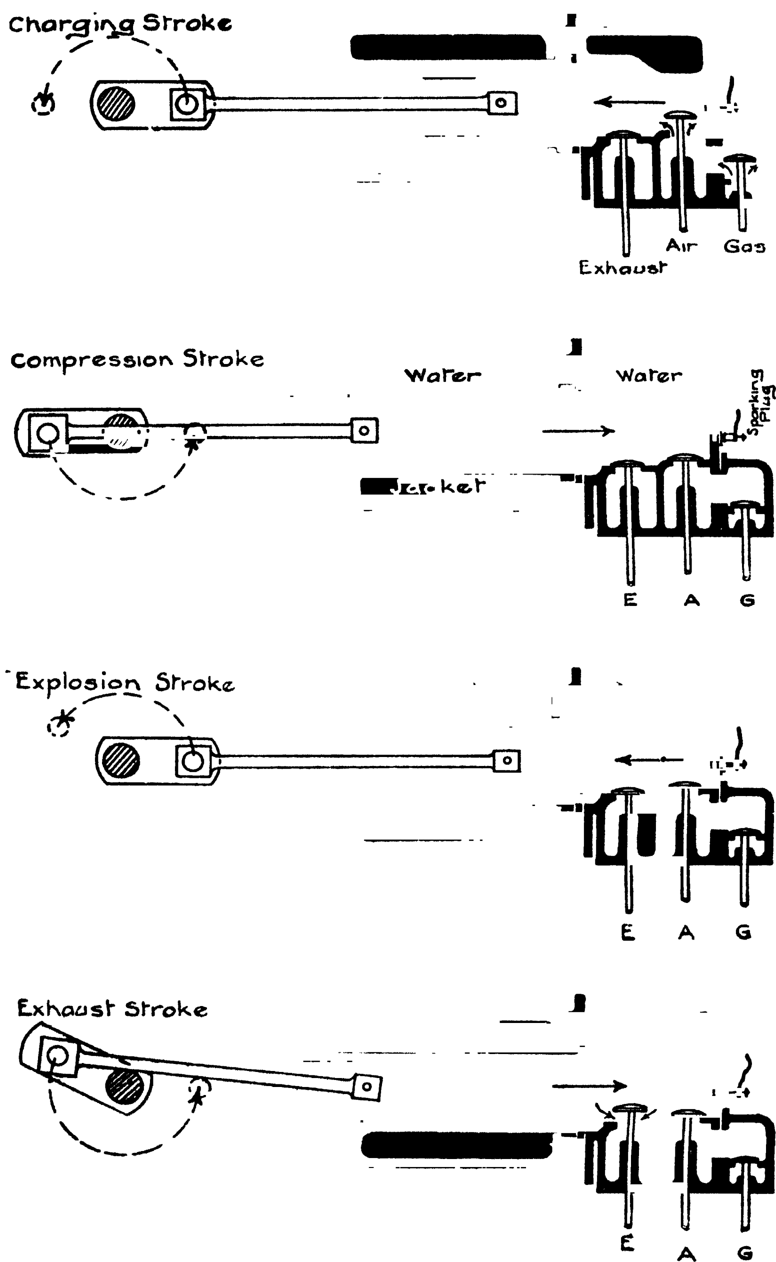


Figure 10. Diagram to show the action of a gas-engine

one half-turn and then stop. But the flywheel, once it has started rotating, takes some time to come to rest, so that it carries the crank-shaft round twice, by which time there is a fresh charge of gas and air in the cylinder, and the piston receives another impulse. An engine of this kind is sometimes called a four-stroke engine, because only one stroke in four is a driving stroke, and a four-stroke engine must have a heavy flywheel to equalize the motion.

It will be observed that the piston is unlike that generally used in a steam-engine. There is no need for a cylinder cover in front, and a bucket-piston is employed. When the piston makes the driving stroke it produces a good deal of pressure on the cylinder walls, and this form distributes the pressure over a wider area.

The valves are of the 'mushroom' type, and are kept on their seatings by springs. They are opened just at the right moment by cams fixed on a shaft which rotates at half the speed of the crank-shaft, and therefore opens each valve once every two revolutions.

The explosive mixture is generally ignited by an electric spark. Electric ignition will be dealt with on p. 58. All engines—steam, gas, or oil—are constructed to run at a certain speed. If the machinery they are intended to drive is more or less idle (i.e. if the 'load' is taken off or reduced), they run away, or 'race', and some form of governor is necessary to keep the speed as constant as possible. The steam-engine governor will be familiar. It cuts off steam when the speed exceeds a certain limit by means of a 'throttle' valve. The gas-engine governor is similar in construction but acts by reducing the supply of gas and allowing a weaker mixture to explode.

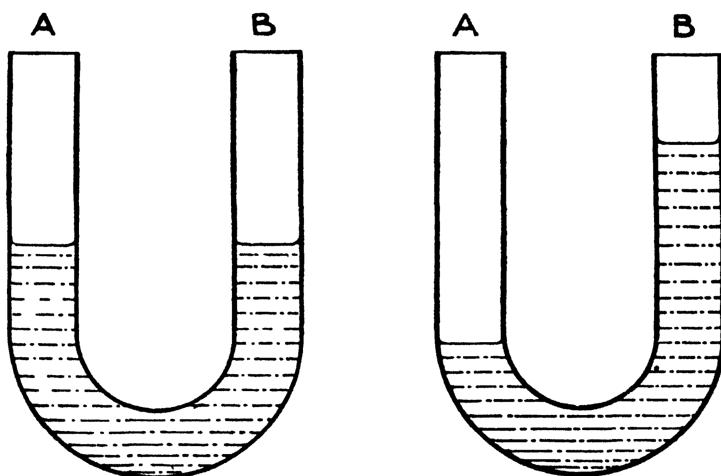
There is one respect in which the internal combustion engine differs from the steam-engine. The cylinders of the latter need to be kept hot to reduce steam condensation, and to this end the cylinders are often 'jacketed' with steam. The internal combustion engine cylinder, on the other hand, tends to become too hot, and the temperature has to be kept down by a water-jacket. Usually the water circulates round and round through the jackets and a cooler or radiator, the same water being used over and over again.

There is, unfortunately, a limit to the size of reciprocating gas-engines, owing to the difficulty of keeping the cylinder and piston cool. Large cylinders are not easy to cast without strain, and the great differences of temperature to which they are subject when the engine is working—a gaseous explosion inside and cold water outside—renders them liable to crack. Some makers cast the cylinder in two or four pieces, and bolt them together. But in a large engine it is necessary to cool the piston also, and this involves pipes with joints that must permit of free movement without leakage. Consequently the limit is about 1,000 h.p. per cylinder.

The real advantages of the reciprocating gas-engine lie in the fact that there are no 'stand-by losses', it can be used with gas prepared from any kind of fuel, and it is thermally twice as efficient as the steam-engine. It will perform any of the work done by a steam-engine within its range, but it is not so steady in running as a turbine and therefore not so suitable for driving electrical generators. Gas-engines of large powers will, in the future, depend on the turbine or jet principle.

THE EXPLOSION PUMP

The reader will recollect how the steam turbine dispenses with all the moving parts of a reciprocating steam-engine except those which



Figures 11 and 12. Diagrams to explain action of the Humphrey pump

rotate, and he will now be prepared to hear of a marvellously simple modification of the gas-engine. In the explosion pump invented by H. A. Humphrey there is no piston or connecting-rod, no crank or flywheel, and only the simplest of mechanisms for controlling the valves.

Suppose a quantity of water is contained in a wide U-tube shown in Fig. 11. If air be forced into the limb A, the water in that limb will be depressed, and the water in the other limb must rise, as in Fig. 12. On removing the pressure the water will flow back until the height in A is very nearly equal to that at which it stood in B, the difference in height being due to friction. This to-and-fro movement, or oscillation, will go on for some time, the height attained at each swing gradually

decreasing. But the time taken for each oscillation will be the same or very nearly so. The smaller the displacement of the water in the first instance the more uniform will the time of the swing be. It depends in any case upon the quantity of water, and can easily be calculated.

Once the water has begun to swing a very slight impulse at the right moment will suffice to keep up the movement. If therefore the end A (Fig. 12) is closed and an explosion of gas and air can be arranged at the moment when the water reaches its highest point in that limb, the water can be kept oscillating for as long as the explosions are maintained. This is the principle upon which the Humphrey pump works. In Fig. 13 the pipe in which the water oscillates, called the play-pipe, is made of cast-iron. It is about 6 ft. diameter, and the horizontal portion is about 60 ft. long. The right limb is open and funnel-shaped, and it has a discharge pipe through which water can flow into the reservoir.

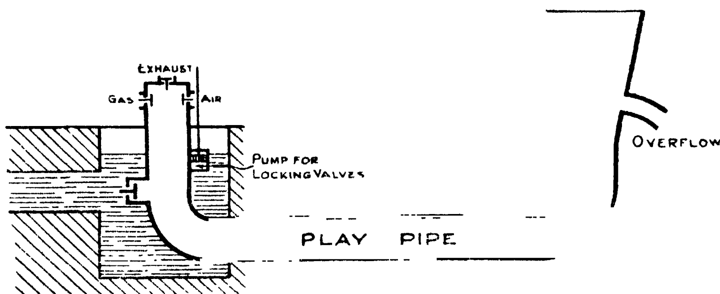


Figure 13. Diagram of Humphrey pump

The left-hand limb is closed by the cylinder, and is built into a well or pit supplied with the water to be lifted. The pump is 7 ft. in diameter and 10 ft. long. Round the upper end are placed two sets of valves for the admission of gas and air, while lower down is a valve opening inwards which admits water. At the top is the exhaust valve. When an explosion takes place the water in the play-pipe is driven forward, rising in the water-tower, and overflowing into the reservoir. Once such a body of water has been set in motion it continues to move after the exploded gases have fallen below atmospheric pressure, and water enters the pump from the pit, replacing in the play-pipe that which has been lost from the discharge pipe. The water in the play-pipe then comes back into the pump and forces the waste gases through the exhaust valves. Having effected this, it flows a second time towards the water-tower, creating a vacuum in the cylinder, and drawing in a fresh charge of gas and air. The return of the water compresses the mixture, which is ignited at the proper moment and forces the water towards the tower again.

All the valves are held lightly to their seatings by springs. They open

and close automatically in obedience to changes of pressure inside the cylinder, and when not required to be in action they are locked by the operation of a small water motor. It will be observed that the strokes are not equal in length. That due to the explosion is a long one, and that which sweeps out the waste gases is longer still. But the charging and compression strokes are short ones. In the ordinary gas-engine, the strokes are all equal. In the Humphrey pump each one is of a length appropriate to, and determined by, the duty it is required to perform.

Such a pump as has been described will deliver from 12 to 14 tons of water per minute. Those erected at Chingford for raising water from the River Lea are five in number, four of them capable of delivering 40,000,000 gallons and one 20,000,000 gallons of water through a height of 25 to 30 ft. every twenty-four hours.

Explosion pumps can be made double-barrelled, and be adapted to give an impulse every two strokes. They can be used as air compressors, in which the moving water acts as a piston, and experiments have been made to apply them to the propulsion of ships. They are simple in construction and therefore low in first cost, require no lubrication, and are economical in working.

PETROL-ENGINES

The earlier inventors who struggled with the problem of the gas-engine were not unaware that the substance used in an internal combustion engine might be supplied in a liquid form, and several of their patents claimed the right to use paraffin or some similar substance in their engines. But it was left for Daimler, who had been for ten years manager of Otto's gas-engine works, to invent the first practical light oil-engine, and his original motor was produced in 1886. Since then there have been many forms differing mainly in detail, but the majority work on the four-stroke cycle described on p. 52. While petrol is the fuel which has been found most satisfactory, others such as benzol and alcohol are sometimes used. The liquid is sprayed into the cylinder or combustion chamber and ignites at the moment when the compression has reached its highest point. The cylinder has to be cooled with water or air. If it is freely exposed, as in the case of a motor-cycle engine, the body has thin fins externally which offer a large cooling surface and water need not be used. With single-cylinder engines a fly-wheel is required to overcome the jerkiness of action, but with several cylinders and cranks set at angles one with another the motion is equalized, and the weight of a flywheel is saved. Apart from variations in general arrangement to suit the conditions under which it will have to work, the chief lines of development have been in carburettors and ignition devices.

The carburettor, Fig. 14, is a device for mixing the petrol vapour with air in the right quantity for complete combustion. There are many forms, but the most usual are provided with a chamber containing a float, the rise and fall of which regulates the amount of petrol flowing from the tank. The petrol then enters a second chamber, into which

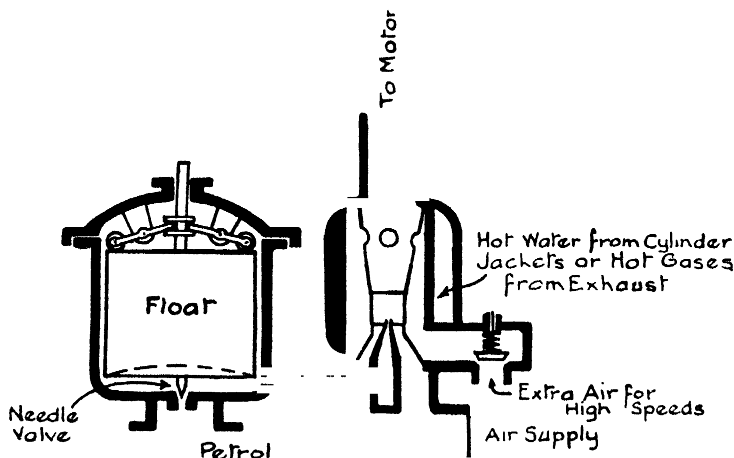


Figure 14. Diagram of a carburettor

it is drawn by the suction of the engine, through a fine jet which converts it into a spray and facilitates an intimate mixture with air. The air enters freely through an open pipe, which permits sufficient to pass for complete combustion under ordinary conditions of working. An additional opening, normally closed by a valve, enables the engine to draw a further supply at high speed.

Satisfactory systems of electrical ignition in internal combustion engines were not developed quickly. Two forms have been used, the low tension and the high tension. The former was invariably produced by a small dynamo called a magneto, driven from the crank-shaft; the latter from a special constructed magneto or an induction coil. The electricity is led into the cylinder through the sparking-plug, at the inner end of which two metal points connected with the wires were separated by the gap in which the spark was formed. One of the best modern types of plug is shown in Fig. 15. It will be observed that the spark can take place between the central rod and any one of the three points surrounding it.

The chief difficulty has been the choking up of the plug with oil and dirt, so that the electricity took the easier path and avoided jumping the gap. This defect has been overcome in a very ingenious way by

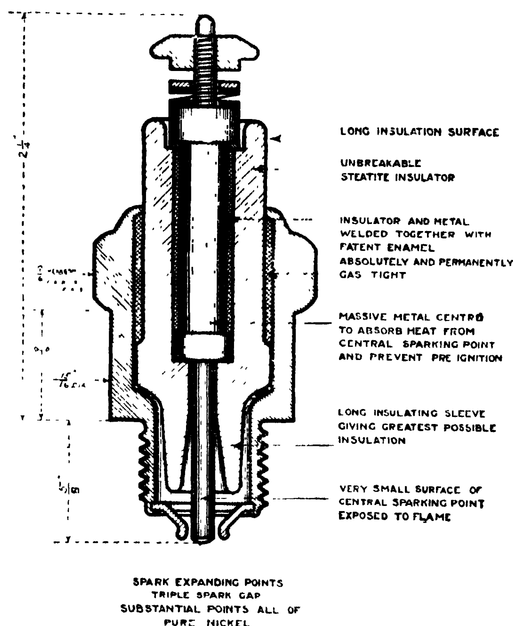


Figure 15. The Lodge sparking plug

Lodge, who employed a special kind of spark. The current produced by an ordinary magneto machine or an induction coil merely jumps across the gap in one direction. It is thin, very little electricity passes at once, and the heating effect is small. But if the terminals between which the spark passes are connected up with some arrangement in which the electricity can be stored, a larger quantity will then pass at once, the spark will be fatter, hotter, alternating, disruptive, and therefore capable of clearing dirt out of the way. In Lodge's apparatus the current is supplied by an accumulator to an induction coil, the terminals of which are connected to the inner coating of a Leyden jar. The outer coating of the jar is connected with the sparking-plug. Fig. 16 shows diagrammatically the arrangement. In Fig. 16 the two balls at A are adjusted so that the electricity flows into the jars until they become, as it were, full, when they suddenly empty across the

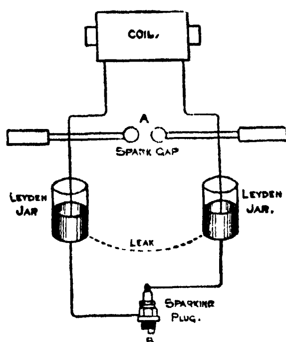


Figure 16. Diagram showing the principle of the Lodge spark

gap. At the same moment a discharge takes place at the sparking-plug. The spark lasts no longer than a millionth of a second, and so violent is it that water, oil, or dirt, though offering an easier path, do not deflect it. A spark can be obtained even when the plug is immersed in water.

The spark is timed by a cam motion. For engines with more than one cylinder a distributor must be employed, so that the explosion in each cylinder may be timed to take place at the right moment. This consists generally of a rotating disc with a metal stud, which makes contact with fixed studs in turn.

The petrol-engine attracted attention from the first by reason of its extreme lightness. It is in locomotion—on rail and road, on sea, and through the air—that it has shown its greatest value.

HEAVY OIL-ENGINES

When gas-engines were first introduced they were of small size, and the cost of town gas prevented their entering into competition with steam-engines of large size. The use of cheap blast-furnace gas, and of producer gas of which the by-products reduced the cost of the fuel, immediately made gas-engines serious rivals to steam-engines for use on land. Similarly both the petrol and medium oil engine, though suitable for marine as well as land use, remained of small size owing to the cost of oil. History has now repeated itself, and an engine capable of using crude petroleum residues has once again revolutionized the production of power—this time both on land and sea.

The achievement is due to Rudolph Diesel, whose long series of experiments resulted in the design of an engine which has been one of the remarkable engineering successes of this century.

Here is an engine requiring no boilers, capable of working with the cheapest oil fuel, which is easily stored, and occupies far less space than an equivalent amount of coal, and capable of undertaking all the ordinary duty that modern manufacture and transport impose. That the advantages were not exaggerated is obvious from the development of the Diesel engine for ships. In 1918 the world's tonnage of motor ships was about 530,000. In 1928 it was about 5,300,000.

It will be interesting to examine the principle upon which the Diesel engine is based. The efficiency of an internal combustion engine depends largely upon the degree of compression. But it will be recollected that when the compression of a mixture of oil or gas and air reaches a certain point ignition takes place, and there is therefore a limit to the compression that can be employed. An air-compressor driven by the engine itself charges a steel vessel with air at 1,000 lb. per sq. in., and this air is used to inject the fuel into the cylinder. This is at such a temperature from

the previous compression that the mixture burns smoothly and rapidly as it enters, expanding by the heat of its own combustion, and producing a steady pressure upon the piston. There is no explosion in the ordinary sense.

Owing to the high pressures employed the engine is very heavily built, and many firms now make what is called a semi-Diesel in which

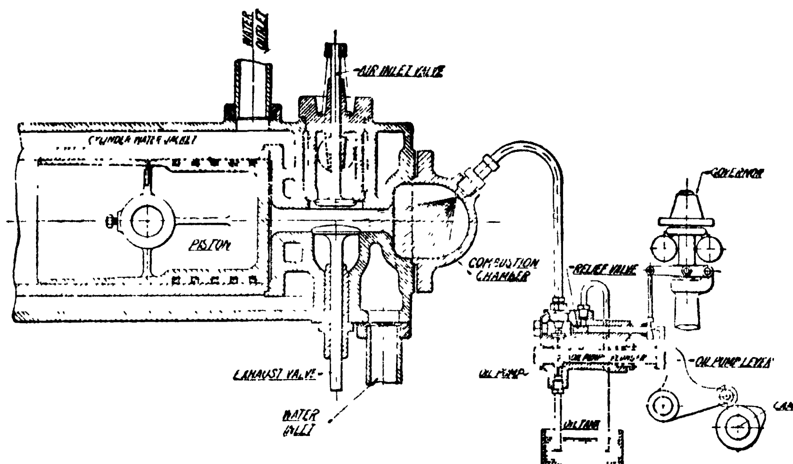


Figure 17. A semi-Diesel engine

the principle is the same (see Fig. 17), but the initial pressures are lower. Both two- and four-stroke engines of Diesel and semi-Diesel types are made.

In reviewing what has been said about the internal combustion engine, it will be seen that its uses range over nearly the whole field for which power is ordinarily required. The small oil or petrol engine is admirable for domestic purposes, such as driving a vacuum cleaner, or pumping water and driving a dynamo to light a house that is far from a town supply; and to cut chaff, mow the lawns, drive milk separators and churns, thresh corn, in places where and under circumstances in which gas power is out of the question. The crude oil-engine again is being used for electric light and power stations, for pumping in waterworks and docks, and for driving the machinery of factories and workshops. In iron and steel works, however, the vast quantity of waste gases from the blast-furnaces and coke ovens renders oil-engines unnecessary. For the motor-car and the aeroplane the petrol-engine, reciprocating or jet, alone stands. Improvements in steel and light alloy manufacture have enabled it to be made so light and yet so powerful that within fifty years two new forms of locomotion have arisen—forms which were dreamt

of for centuries and have now emerged into a vigorous development. In this progress the usual order of events is to be observed. A new discovery or invention which ministers to comfort, convenience, or efficiency is at first available only for those who can afford the heavy capital outlay which its possession involves. But, sooner or later, according to the public service it can perform, this is brought by public supply within the reach of many whose needs outweigh their private resources. Thus, the private car has been followed by the commercial vehicle, the taxi, and the motor-bus. But in the case of the aeroplane, as we shall see later, a public service has anticipated any large development of personal enterprise.

In other forms of transport the internal combustion engine is proving of equal value. The petrol-engine has been used in launches as long as it has been used in motor-cars, and fleets of ships are now equipped with Diesel engines. Coal-burning under steam boilers is wasteful of valuable by-products, but oil-power requires not only an adequate supply of fuel, but also the necessary depots at ports of call from which a fresh supply can be obtained.

Internal combustion engines have, however, one defect for marine purposes, which they share with the steam turbine: they are not easily reversible. They can be constructed to run in either direction, but reversal is not so simple and quick as in the case of the reciprocating steam-engine.

THE MERLIN AERO-ENGINE

The air-battles of the Second World War were fought with reciprocating engines. Chief among these was the Merlin engine, evolved by the Rolls-Royce Company. By the end of the war in Europe, 150,000 Merlin engines had been produced (Plate XIII*a*).

The Merlin engine was the outcome of many years of engine development by the Rolls-Royce firm. The characteristics of this firm's work had been established by Royce in the creation of his motor-manufacturing company. As described in Chapter XV, F. H. Royce was an untutored, self-educated engineering genius, whose great achievements were due to an extraordinary capacity for taking pains. He did not invent new kinds of machines or engines, he was not a Lanchester or a Whittle. He took a conventional engineering product and made it better than any other, by incorporating the best points of other designs, and then perfecting every part by a relentless attention to detail.

He had started his first motor-manufacturing through the accident of buying a second-hand motor-car in the 1890's. He founded his aero-engine manufacturing through a similar accident.

The German declaration of war in August 1914 found the British

very ill-prepared in many directions, including air warfare. Royce himself had concentrated entirely on his motor-cars. When approached by the Admiralty to manufacture certain aero-engines of foreign design, he severely criticized the design, and rejected the invitation. His works was closed for the annual holiday when news of the declaration of war was announced. Under the assumption that war meant ruin for their luxury industry, the firm cancelled all its orders, sacked half its staff and cut the salaries of the remainder by half. Presently they recovered from the panic, as demands for cars for military staff came in, and they had trouble in reassembling the highly-skilled staff that they had dispersed.

The military authorities were, however, seriously worried at the prospect of the new air warfare, and the progress that the Germans might have made in it. Just before the outbreak of the 1914 war, the Mercedes cars had won a spectacular victory in the Grand Prix motor race in France. It was known that engines of these cars were the prototypes of the aero-engines that the Germans intended to use in aerial warfare. The Mercedes firm had, however, in their pride of performance, sent one of their winning cars to be exhibited in London, and had not had time to withdraw it owing to the suddenness of the outbreak of war.

In the national emergency, Royce now consented to consider the production of aero-engines, but though he had unsurpassed achievement in motor-engine manufacture, he had no experience whatever in aero-engine design. A search for the exhibited Mercedes engine was therefore made. It was found hidden in a cellar. It was immediately sent to Derby, where it was dismantled, and drawings made of every part in the minutest detail.

The engine was then reassembled, and tested until it broke down. Royce with his peculiar genius went over every part, making improvements here and there, and then designed his first aero-engine. It was a twelve-cylinder V-engine, with two banks of six cylinders, inclined at 60 degrees, the prototype of the 'Eagle' engine. It was liquid-cooled, with cylinders of bore and stroke $4\frac{1}{2}$ in. by $6\frac{1}{2}$ in. This engine, constructed within six months in 1914–15, established the characteristic features of Rolls-Royce reciprocating aero-engine design for the next thirty years, and culminated in the Merlin engines. It is a remarkable demonstration of Royce's engineering insight and judgment.

Just as he had started his motor-car design from a French car, he started his own aero-engine design from a German engine which had been sent to him. He was able to take a design and see, as it were, right down to its foundations, and upwards to its ultimate possibilities.

In the period 1914–24, 4,676 Eagle engines were made. They were mainly used in bombers and heavy aircraft. The lighter 'Falcon' twelve-cylinder V-engine was evolved for fast aircraft, and was used in the famous Bristol fighter.

Royce's engines were named after birds of prey: the 'Merlin' engine was named after the bird, not the magician, as many believed after its wonderful performances. The 'Eagle' was used to engine the machine with which Alcock and Brown in 1919 made the first non-stop crossing of the Atlantic. It had a very narrow cross-section, being narrower than the pilot, and hence the fuselage that carries it can be very narrow, thus reducing air-resistance to the minimum.

The next big stimulus to Royce's genius in aero-engine design came from the preparations for the Schneider Trophy Races of 1929 and 1931. He was asked to produce an engine capable of winning the race, and he selected one of his 'Buzzard' engines, a bigger 'Eagle', for development. Its power output was to be increased for only a small increase in weight. He fitted these R-engines with a larger supercharger, increased the compression ratio and revolutions. When the R-engine was raced, it gave 1,900 h.p. at 2,900 r.p.m., for a weight of 1,530 lb.

The life of these engines running at these speeds was raised from twenty minutes to one hour. Finally, one was ready, and fitted into the Vickers Supermarine seaplane designed by R. J. Mitchell. The machine won the 1929 race at an average speed of 328 m.p.h.

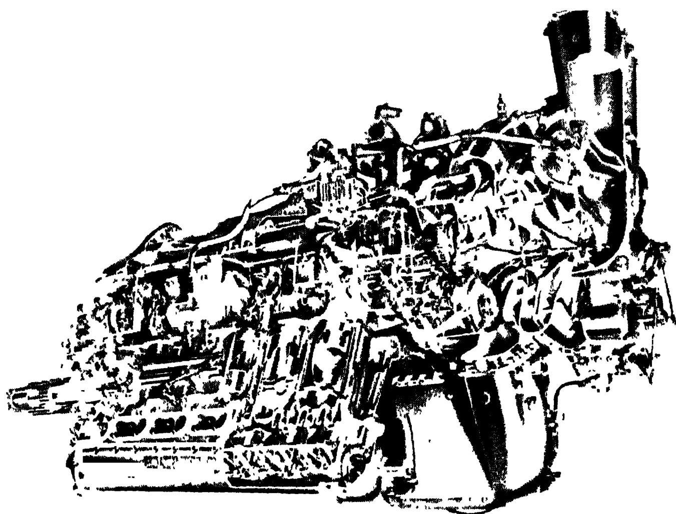
For the 1931 race, the R-engine was further strengthened, and the air intake and engine-speed increased. In April 1931, the engine lasted for only twenty minutes at full power. By August 3rd, its life had been raised to 58 minutes, producing 2,360 h.p. at 3,200 r.p.m. for a weight of 1,630 lb. The 1931 engine was 21 per cent more powerful than the 1921 engine, for an increase of only 6½ per cent in weight. Installed in one of Mitchell's seaplanes, it won the Schneider Trophy outright.

Thus already, in 1929 and 1931, the geniuses of Royce and of Mitchell had come together, and had laid the foundations for Mitchell's 'Spitfire' powered with a Rolls-Royce Merlin engine.

Royce died in 1933, but he had made his fundamental contribution. He and his colleagues had laid the foundation of British aero-engine superiority which was one of the factors which decided the result of the Battle of Britain in 1940.

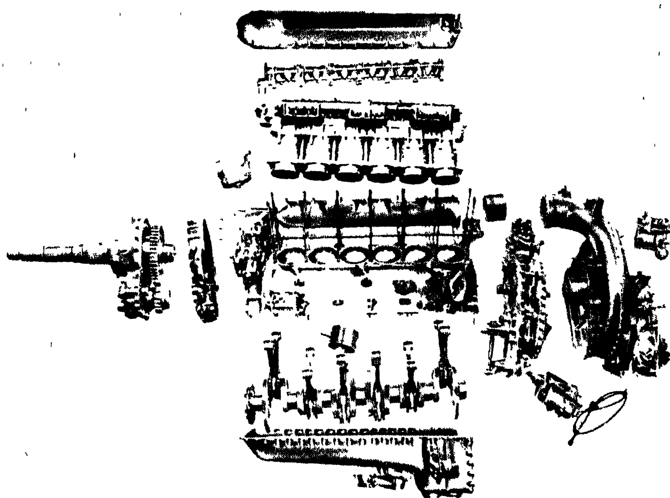
Besides contributing a unique combination of thoroughness, accuracy and perfection, the increasing preoccupation of Rolls-Royce with supercharger design provided the firm with part of the experience which enabled them subsequently to attain the lead in the development of the turbo-jet engine, the compressor of which is a development and adaptation of supercharger design.

In 1932, just before Royce died, Rolls-Royce decided to evolve a standard engine from the racing engine that had won the Schneider Trophy. Its main characteristics were laid down by Royce, and the first drawings were begun in January 1933, the month in which Hitler became Chancellor of Germany. By December 1933, the new engine had



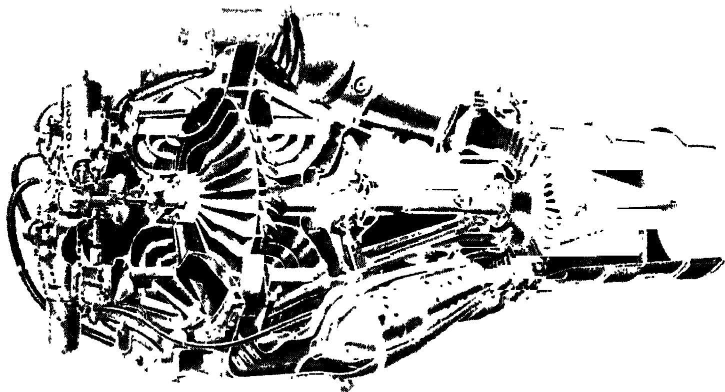
(Rolls-Royce)

XIIIa. The Rolls-Royce Merlin 620 aero H engine



(Rolls-Royce)

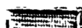
XIIIb. Sub-assemblies of parts of the Griffon engine; a larger Merlin 6-in. bore by 6½-in. stroke, weight 2,100 lb.

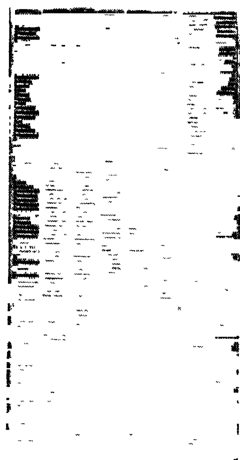


(Rolls-Royce)

XIVa. Section of the Rolls-Royce Derwent turbo-jet engine







XIVb. Single negative element and plate, and set of plates of an accumulator

been built and tested, after surmounting many difficulties with persistent cracking of cylinder jackets, and other troubles. On test, it was rated at 955 b.h.p. at 2,600 r.p.m. at 11,000 ft., and 1,045 h.p. at 3,000 r.p.m. at 12,000 ft. It was put into production as 'Merlin I'.

The first flights were made with the new engine in 1935. The coolant used was changed from water to glycol, which allows the cooling system to work at 150° C. instead of 80° C.

The new engine had outpaced British aircraft design. In the existing aircraft more power was of no advantage, for increased speed more than proportionately increased the resistance. In order to get a more advanced aircraft of 'cleaner' aerodynamical design, the Rolls-Royce firm made a deal with the Heinkel company. They bought an He. 70, and sent one of their older 'Kestrel' engines to Germany, to be installed in it. The Germans made exhaustive tests on the 'Kestrel' before the machine was returned to England.

The prototype of the 'Spitfire', with a Merlin engine, was flown for the first time in February 1936. R. J. Mitchell's original design had followed the lines of a gull-shaped Heinkel, but when the machine was made, it gave a disappointing performance. Mitchell scrapped this design, and went back to his successful Schneider Trophy design.

In June 1934, preparations were begun for an attack on the world speed record with a special 'Spitfire' and a Merlin III engine, taken from stock. The pistons, gudgeon pins and connecting-rods were strengthened. The standard engine gave 1,030 b.h.p. at 3,000 r.p.m. at 10,250 ft., with a 'boost' (i.e. air intake delivered to the engine by the supercharger), at 6¼ lb. per sq. in. pressure. By opening the throttle, raising the boost, and using fuel with a higher octane number, the b.h.p. was raised to 2,160 at 3,200 r.p.m., and 27 lb. boost. With this engine, the special Spitfire reached 404 m.p.h. at 500 ft.

Owing to the threat of war, however, the attempt on the speed record was never made. The machine was subsequently used for photographic reconnaissance during the war.

The development of the Merlin engine depended more and more on the development of the supercharger. Ultimately, the centre of interest moved from the reciprocating part of the engine to the supercharger. From the evolutionary point of view, the supercharger was the new shoot, destined to survive, while the original main part of the reciprocating engine, the cylinders and reciprocating mechanism, began to become vestigial and destined to extinction. The supercharger became more and more important, and passed on to a new life of development in the turbo-jet engine, after the reciprocating mechanism had disappeared altogether.

The original need for the supercharger arose from the fall in pressure of the air with the rise of altitude. When an ordinary engine is taken up

in an aircraft, it produces less and less power, because the weight of air going through the engine decreases. The power developed by the engine depends on the *weight*, and not on the *volume* of air passing through it. At greater heights, then, it is necessary to compress the thin air sucked in from the atmosphere, so that it is more dense, before it enters the engine. The engine is given, as it were, not the ordinary charge of air that it would have sucked in by itself, but a supercharge of air, delivered by the auxiliary compressor. For this reason, the auxiliary compressor is named the 'supercharger'. The compressor consists of a centrifugal blower. By adding to, or 'boosting', the intake pressure, the engine-power at take-off can be increased. At high altitudes, the compressor has to run more quickly in order to compress the thinner air. Thus the supercharger is provided with a multi-speed drive in order to adjust the blower to the appropriate speed. In a later form, the supercharger works in two stages, consisting of two rotary compressors in series.

At high altitudes, the supercharger is put into the high speed gear. The mixture of air and petrol vapour is raised to a high pressure, and, incidentally, to a high temperature. In order to reduce the temperature, which would otherwise reduce the efficiency of the engine, and cause danger of pre-detonation of the explosive mixture, the compressed gas is passed through coolers before it is delivered to the engine-cylinders. In the Spitfire, the radiator for the supercharger cooling system was placed under the wing.

The Rolls-Royce development of the supercharger enabled British aircraft to operate at a height of eight miles above the earth's surface.

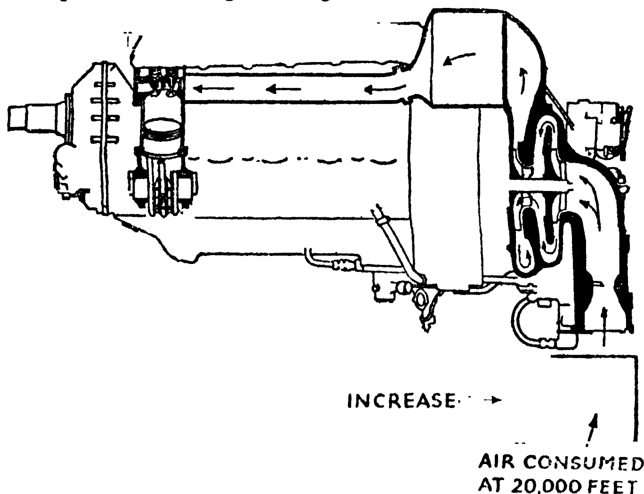


Figure 18. Two-stage supercharging

The maximum rotational speed of the supercharger impeller exceeded 25,000 r.p.m.

In the Merlin 620, each cylinder block is made of a light alloy cylinder skirt and head. A special wear-resisting steel liner is fitted in, to bear the sliding motion of the piston. The coolant is circulated around the outside of the steel liner.

Each cylinder has four valves. Two are inlet valves, and two are sodium-cooled exhaust valves. The crankshaft runs on seven lead-bronze lined main bearings. The connecting-rods are H-shaped steel forgings.

The two rotors of the supercharger are driven through three clutch-wheels, in order to absorb stresses caused by rapid acceleration. Torsional fluctuations are absorbed by a spring-drive shaft.

The main cooling system, cooling the cylinder blocks, is operated on a mixture of water and glycol. This is prevented from boiling by keeping it under pressure.

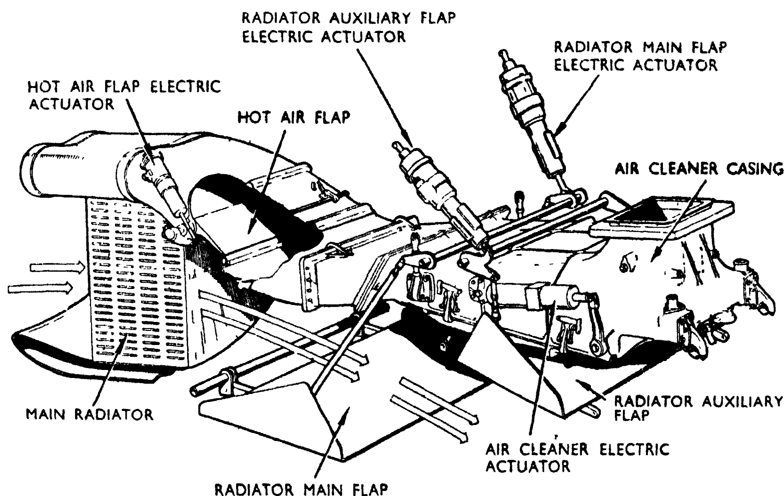


Figure 19. Radiator flaps and air intake system on the Rolls-Royce Merlin

The radiator is placed so that it can be used for warming the intake air when the aircraft is flying under icing conditions. For flying under dusty or sandy conditions, the duct conveying the intake air contains large filters made of felt, which can be brought into operation to cleanse the air, if necessary.

Lubricating oil is pumped through an extensive system of internally drilled passages to the various engine components, the flow being proportioned to the various needs. The oil is cooled by passing through a cooling system. Thus there are three distinct cooling systems in the engine.

Fuel is injected into the engine by a pump. Rolls-Royce, like other British engineers, stuck to the carburettor, until forced to change by German superiority in vertical dives. These upset the carburettor, whereas the injection pump was unaffected by them.

It consists of a pump with five plungers. The stroke can be varied by a swash-plate. The swash-plate assumes a mean position in reply to the engine's demands through a servo-mechanism.

The engine and its auxiliaries, forming the complete power unit, is enveloped in a streamlined casing.

In 1950, one thousand Merlin 620's were in service on civil airlines.

The engine contains about 11,000 separate parts, 4,500 of which are of different shapes. About 47 per cent by weight consists of steel, and 43 per cent aluminium, with small quantities of other metals in alloys, and some 7 per cent of non-metals.

The Merlin reciprocating engine was at the end of a period of evolution in reciprocating engines. It had achieved an extraordinary degree of complication and refinement. The Rolls-Royce Company had already made long steps even beyond it, with a 24-cylinder sleeve-valved reciprocating engine, with its cylinders arranged in four banks of six, in an H-form. It was nominally rated at 3,500 h.p. The 'Exe' engine had 24 cylinders in the form of a cross.

But these were already the dinosaurs of the reciprocating-engine world. They have been superseded by the far simpler, far more powerful jet engine. It was very remarkable that such a complicated engine as the Merlin could be made to work so well, and even be mass-produced, but it contained within itself the growing seeds of its supersession. The supercharger grew more and more important and survived, while the reciprocating engine itself began to pass away.

In aero-engine development, technique gradually advanced until it was able to master the complication of such engines as the Merlin. In overcoming the problem of the completion of reciprocation, it fitted itself to solve a new problem, to overcome the different and deeper difficulties of utilizing jet propulsion.

Not only was the production of Merlin engines solved, it was reduced to mass-production methods, largely by skilled labour. This was due to the development of high-precision automatic tool-making.

The Rolls-Royce Company greatly increased its production during the war, building additional new factories at Crewe and Glasgow. In 1943, with a staff of nearly 60,000 workers, they were manufacturing Merlin engines at the rate of 18,000 a year. The Ford Company was making 200 Merlins a week, and in the United States Packard was making 100 a week. In the Ford works at Manchester, more than one-third of the workers were women.

The high quality of the innumerable parts was kept up by stringent

inspection. Nearly one-tenth of the total staff consisted of inspectors, 5,000 altogether.

JET ENGINES

The jet engine is the oldest type of heat-engine for producing power. Hero of Alexandria, who lived at about the beginning of the Christian era, left a description of a machine consisting of a sphere mounted on a hollow axle. Steam was admitted to the sphere through the axle, and escaped through two bent tubes at the opposite ends of a diameter at right angles to the axle. The exits to the two tubes pointed in opposite directions, and were parallel to tangents to the sphere. As the steam spurted out of the tubes, steam and tubes moved in opposite directions. The tubes thus caused the sphere to spin on its axle. This contrivance was probably a toy.

Since Hero's time, two thousand years ago, jet propulsion has been proposed and experiments made with it many times. Isaac Newton himself suggested in 1680 that a carriage might be propelled by the reaction from a jet of steam. The reaction from a jet of steam is utilized in the Parsons and other reaction steam turbines.

Jet propulsion is used in rockets. These are propelled by reaction from the escaping jet of explosive gases spurting out of the case. This method of propulsion is probably as old as the invention of gunpowder and fireworks by the Chinese.

Though jet propulsion is ancient, it has only recently become of great practical importance, because of the difficulty of making it efficient. This became possible only after science had advanced sufficiently to give a deep analysis of its problems, and technology could make the machines which could utilize efficiently the power produced by jets. The two sciences which have enabled jet propulsion to become of major importance are aerodynamics and metallurgy.

The engineer whose genius has led British work in jet propulsion is Sir Frank Whittle. He joined the Royal Air Force as a boy, and had already in his youth envisaged the modern jet engine. He was sent by the R.A.F. to Cambridge to receive a first-class engineering training so that he had the scientific equipment to carry his ideas out. He filed a patent in 1930 for a jet engine, and after eleven chequered years of struggle, an aircraft powered with one of his engines flew for the first time in May 1941.

In the piston engine for aircraft, the fuel is burned inside the cylinders, and its energy is communicated through pistons to the turning of a shaft. This bears a propeller, that draws the aircraft forward through reaction against the air. It is a complicated system.

Jet propulsion is in principle much simpler. The energy of the fuel

is communicated directly to air, making it spurt backwards at great speed, and thus thrust the aircraft forward by reaction.

As the air is caused to flow at very high speed, the amount that has to be energized by the fuel is much less than the amount of air that has to pass through a propeller.

The high-speed piston-engined aircraft is at the end of its evolution. In a Mosquito aircraft, for instance, no less than 20 per cent of the propulsion already comes from reaction from the jets of gas from the exhaust pipes. In such a machine, the source of power is already beginning to move, as it were, from the pistons to the exhaust pipes.

In piston engines the burning fuel-air mixture is drawn out of it through the operation of a four-stroke intermittent cycle. In the jet engine the energy produced by the burning of the fuel is conveyed directly and continuously into the flowing mass of air that emerges from the jet.

In principle, the piston engine is very clumsy; the jet engine is smooth and elegant. But in practice it is very difficult to take advantage of this superiority in principle. Fundamentally, this is due to the lightness and tenuity of air and gases. A piston cylinder is a clumsy contrivance, but the light gases inside it are under complete control. They are used as a medium for the transfer of energy to the piston.

In the jet, the power comes from gases in very swift motion. A mass of gas is a tenuous and voluminous thing, and if it is moving at high speed it is very difficult to control, and it cannot be controlled efficiently without a deep insight into the science of the flow of gases, of aerodynamics.

In Whittle's turbo-jet engine, manageability of the air is increased by compressing it before it is burned. The air intake is compressed partly by the forward rush of the aircraft, but mainly by a compressor. After the air is compressed, it flows towards a combustion chamber. Fuel is pumped into it, and as it flows on, the machine is fired by an igniter. The burning produces heat, which causes a rise of temperature and pressure, and hence of the speed of flow of the gases. These pass through the blades of a turbine which provides power for driving the compressor. They continue on, into a large conical exit pipe, much wider at the exit than at the annular space across which the turbine blades revolve. Thus the gases expand, their temperature falls, and the heat-energy of the fuel becomes almost completely transformed into the energy of the flowing mass of gas moving as a whole. The efficiency of a jet engine is measured by the fuel used for a given thrust.

The Rolls-Royce Derwent is a fine example of a turbo-jet engine. Its gas flow diagram is shown in Fig. 20.

On the top black line, the increase of velocity of the gas as it proceeds through the engine is given at the various stages, being emitted from the jet with a velocity of 1,200 m.p.h.

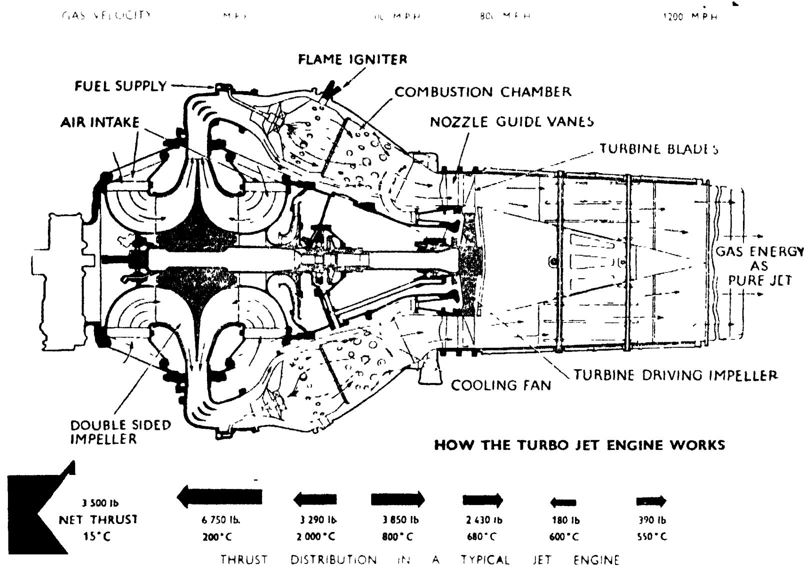


Figure 20. Gas flow diagram of a Rolls-Royce Derwent turbo-jet engine

When the engine is running at ground level, the air is drawn into the compressor at 200 ft. per sec., and passed on at 290 ft. per sec. Its temperature is raised from about 13° C. to 207° C., and pressure from 14·4 lb. per sq. in. to 61·6. The air passes into the combustion chamber at 290 ft. per sec. and is discharged into the turbine at 550 ft. per sec. Its temperature is raised from 207° C. to 837° C. and its pressure falls from 61·6 lb. per sq. in. to 58.

The gas enters the stationary blades of the turbine with an axial velocity of 550 ft. per sec. and leaves the exhaust with a velocity of 1,250 ft. per sec. The temperature falls from 837° C. on entering the turbine to 612° C. at the turbine exhaust. Meanwhile, during expansion through the turbine, the pressure falls from 58 lb. per sq in. to 20.

Most of the expansion in the turbine takes place through the nozzle guide vanes. This produces a very swift 'whirl' in the gas, charging it with energy of movement derived from heat converted through fall of temperature.

The 'whirl' and its energy is then taken out of the gas by flow through the turbine blades. These cause the shaft to rotate and drive the compressor at the other end.

The final expansion and increase in the gas velocity occurs through the jet pipe. The gas from the turbine exhaust enters it at 1,250 ft. per

sec. and finally leaves the jet pipe, and the engine, at 1,800 ft. per sec. The temperature falls from 612° C. to 550° C., and the pressure from 20 lb. per sq. inch to 14·7.

The gross thrust developed by the engine is the sum of all the positive and negative thrusts developed at various stages in the engine, and shown in thrust distribution in Fig. 20.

When the aircraft powered by the engine is in flight, the net thrust is equal to the gross thrust less the momentum drag due to the stream of intake air.

The rotation of the engine is anti-clockwise, viewed from the rear. Its weight, including starter motor and oil tank, is 1,280 lb., i.e. only half a ton. The maximum diameter of the engine is only 43 in., and length 83 in.

Through the centre of the engine is the shaft bearing the compressor disc and the turbine wheel. The whole is called the rotating assembly.

It is very carefully balanced. Friction is reduced to the minimum by roller bearings. These are flushed with anti-freeze lubricating oil at a pressure of 30 lb. per sq. in. The engine is capable of running perfectly for long periods, without rise of temperature in the bearings, even when the lubricating oil has been shut off.

When the engine is developing its maximum static thrust, the compressor deals with 62 lb. of air every second. The compressor disc, or impeller, has vanes on both sides, so that the reactions from the two sides exactly balance each other. The air passes axially through guide vanes which give it an initial whirl in the direction of rotation, and is then flung outwards along the appropriately curved guide vanes on the swiftly-revolving disc. The impeller disc is 24½ in. in diameter, and has 29 vanes on each side. At full speed it absorbs 8,000 h.p., which is being generated by the turbine. This consists of a forged disc of a special high tensile stainless steel which is resistant to 'creep' at high temperatures. It is broached to receive the roots of the turbine blades, which are made of the alloy 54 Nimonic 80.

At 4,200 lb. thrust, the Derwent V engine develops 12,000 h.p. in an aircraft travelling at 600 m.p.h. Its turbine then runs at 15,000 revolutions a minute, and is capable of accelerating from an idling speed of 2,500 up to 15,000 r.p.m. within four seconds. The speed of the tips of the blades of the impeller is then 1,100 m.p.h., which is faster than that of a rifle bullet.

The tensile stresses on the blades of the impeller and turbine are enormous, and in the case of the turbine blades, are combined with very high working temperature. The production of metals and alloys which will withstand these conditions is one of the greatest achievements of modern metallurgy.

The compressor delivers the compressed air to nine combustion

chambers arranged symmetrically around the impeller disc. The successful design and construction of the combustion chambers was one of the most difficult of the many problems in jet-engine development. Slight changes in the shape and flow of the gases have a profound effect on the efficiency of the system. Each combustion unit consists of a light alloys expansion chamber leading to an aluminized mild steel casing. The incoming stream of air swirls around a burner through which fuel enters the chamber. A secondary supply of air is pumped into the chamber through holes in the sides, to form a cool blanket which protects the metal where the combustion flame is at its hottest, up to 2,000° C.

Each chamber is connected with its neighbour, so that if the burning is started in one chamber by an igniter torch, it lights up the flame in the others.

Duple burners in each chamber are fed by two independent streams of fuel, a primary stream through a small pipe, and a main stream through a larger pipe. At low speeds, and starting, the main stream is shut off. Though the flow of fuel is low, it is atomized into a fine spray and blown through each of the burners, providing easier conditions for igniting and starting the flame. As the rate of fuel flow increases, the main stream is brought into operation (Plate XIV*a*).

The Rolls-Royce Nene engine is an improvement on the Derwent V. It develops a thrust of 5,000 lb. and has a diameter of 49½ in. At full power it consumes 800 gallons of fuel per hour.

The Rolls-Royce Avon jet engine develops a static thrust of 6,500 lb. at sea-level. In order to keep the diameter low, so that the drag of air resistance on the aircraft should be as low as possible, an axial flow compressor has been adopted in this engine. The diameter is 42·4 in. and the length 119 in.

A Meteor jet aircraft powered by Avon engines can rise to 40,000 ft. in less than four minutes.

Aero engines are used in the 'Canberra' standard medium bomber of the Royal Air Force. One of these machines crossed the North Atlantic Ocean in 4 hours 37 minutes, without refuelling.

The 'Comet' airliners produced by the de Havilland Aircraft Company, which are transforming long-distance travel, are powered with four Avon engines.

V

GENERATION AND TRANSMISSION OF ELECTRICITY

THE nineteenth century was the age of steam. The twentieth century is the age in which he who controls the generation and distribution of electricity holds the key to most of the operations of industry. One of the greatest values of electricity lies in the ease with which it can be transmitted by a wire overhead or underground. In this way, power can be produced at one centre with the economy that always attends operations on a large scale, and can be utilized in places where water is not available and where the hiss of steam or the cough of an internal combustion engine would be impossible or undesirable.

MAGNETS AND ELECTRIC CURRENTS

In attempting to give some account of the way in which electricity is produced and distributed it is first necessary to recall a few elementary facts of electrical science. A magnet is a piece of steel possessing properties which cause it to take up, when freely suspended, a north and south direction. The end turning towards the north is called a north pole, and the opposite end a south pole. Between the poles in the space surrounding the magnet a force is exerted along definite curved lines, and these curves can be rendered visible by scattering iron filings on a paper laid over the magnet. These arrange themselves in definite directions which are indicated for different cases in Figs. 21, 22. The presence of other magnetic substances in this 'field of magnetic force' causes distortion; the lines gather up and pass in greater number through soft iron than through any other substance. The curved lines are supposed to be continuous through the magnet, but the chief internal effect of importance to the electrical engineer is the permeability, which is measured by the ease with which the force is produced in the material.

Two magnets exert a force upon one another, according to the law that like poles repel and unlike poles attract. This is only another way

of saying that the magnets act on one another in such a way that the lines of force of each may run in the same direction, and as far as possible through iron or steel all the way. The tendency for the force

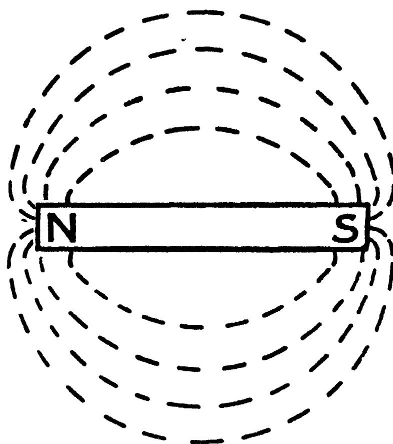
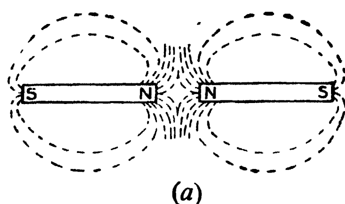
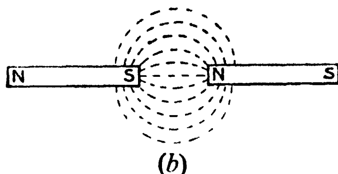


Figure 21. Magnetic field of a bar magnet



(a)



(b)

Figure 22. Magnetic fields of a pair of magnets: (*a*) like poles, (*b*) unlike poles

to pass through iron or steel creates a tendency for the iron or steel to move into such a position that the greatest amount of magnetism is produced within it.

When steel is once magnetized it retains more or less unimpaired the properties which it has acquired. Soft iron, however, only possesses these properties so long as it remains in a magnetic field, acting in these circumstances as a temporary magnet. At the same time, since the earth is a magnet, most varieties of iron or steel have some residual magnetism.

Whenever therefore a piece of soft iron is placed in a magnetic field so that lines of force pass through, it acquires temporary polarity at the points where the lines enter and leave the material. The soft iron is then said to be magnetized by induction. The terms soft iron and steel have not now the significance that was implied twenty or thirty years ago.

Soft iron is a somewhat rare material, and steel can now be obtained which exhibits a very wide range of 'retentivity' or power of retaining

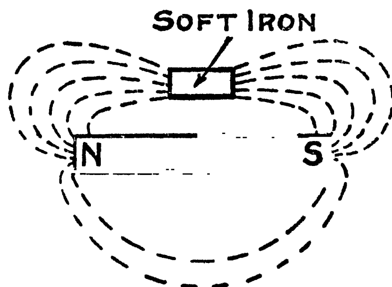


Figure 23. Influence of a piece of soft iron on a magnetic field

magnetism, while some iron alloys are even non-magnetic. Other substances than iron and its alloys are capable of being magnetized, but not to anything like the same extent.

Now at this stage let it be taken for granted that an electric current can be produced and sent through a metal wire. This wire must form part of a continuous circuit or loop; if it be broken at any point the current will cease to flow. It should be covered with cotton, silk, rubber, or one of the many substances which offer a large resistance to the passage of electricity, for the latter tends to cut across the shortest path. All metals and water may be regarded as conductors, and most other materials such as paper, wood, oil, and those mentioned above as non-conductors or insulators, though all insulators will break down under a sufficiently high electric stress. Magnetic force, on the other hand, is exerted freely through all these bodies, the only material which has any appreciable effect upon it being iron and its alloys.

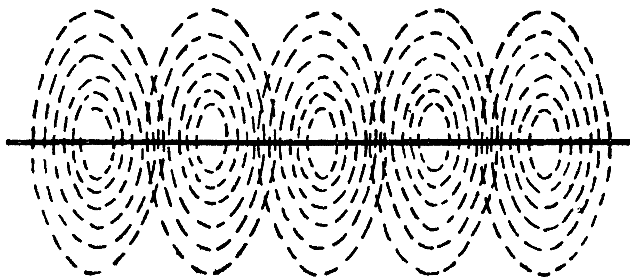


Figure 24. Magnetic field of a straight wire carrying a current

A wire carrying an electric current possesses the same properties as a magnet, only in this case the curves which represent the direction of the

force are circles whose planes are at right angles to the direction of the wire, as in Fig. 24. If the wire is coiled into a ring, Fig. 25, then one face tends to turn towards the north and the other towards the south pole, so that the plane of the ring becomes east and west. If the wire is coiled

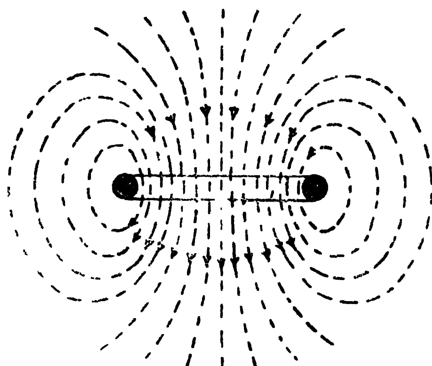


Figure 25. Magnetic field of a single coil

in a spiral so as to form a number of rings side by side, then the whole coil acts like a long magnet, and if freely suspended turns so that its axis points north and south, Fig. 26. Such a coil or 'solenoid' is more powerful with the same current if it is provided with a soft-iron rod or

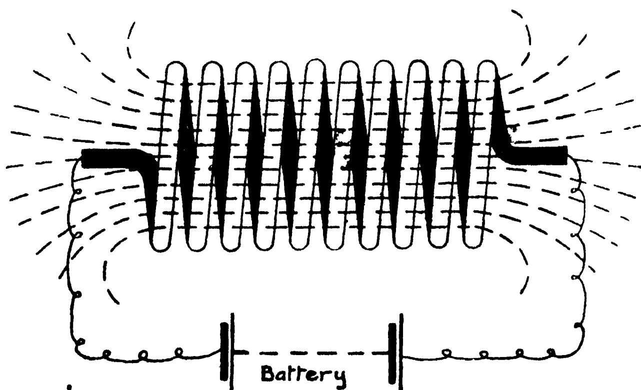


Figure 26. A solenoid and its magnetic field

core, which gathers up and concentrates, as it were, the magnetic force inside the coil. The effect of such a coil decreases with distance, in the same way as a magnet. If the current is increased the rings may be supposed to expand outwards, and if it is decreased or stopped they

may be regarded as closing up until they disappear into the wire from which, apparently, they emerged.

The wire carrying a current is, in fact, surrounded by a magnetic field, and a small freely suspended magnet brought near to it tends to set itself at right angles to the wire. A galvanoscope or galvanometer consists of a coil of wire above or below or within which hangs a small magnetic needle. Each turn of the coil produces its own field and contributes its own force to turn the needle at right angles to the plane of the coil. If the current is reversed the movement of the needle is reversed, and if the coils are large and circular, and the needle small, an exact measurement of the force exerted can be made. This magnetic effect in turn affords a means of calculating the strength of the current in the coil.

THE MEASUREMENT OF ELECTRICITY

Just as it is impossible to obtain any clear idea about steam-engines without speaking of temperature and pressure, so it is necessary to describe an electric current in definite terms. The strength of the current, which governs the magnetic effect, is measured by the quantity of electricity which flows through any cross-section of the wire per unit of time,[1] and it is convenient to suppose that there is some force tending to drive electricity through the wire. This force is called *electro-motive* or e.m.f., and is measured in *volts*, so called after the famous Italian physicist Volta. Different substances offer different degrees of *resistance* to the passage of electricity, and the resistance is measured in units called *ohms*, after another of the early workers. The strength of the current produced by an electro-motive force of 1 volt acting through a resistance of 1 ohm is called 1 *ampere*, after a celebrated Frenchman. If E is the number of volts, I the number of amperes, and R the number of ohms resistance of a wire, then

$$I = \frac{E}{R}$$

Similarly the total quantity of electricity in a given time is measured in units, each equal to 1 volt multiplied by 1 ampere. This unit is called a watt, and 1,000 watt-hours is a Board of Trade unit of electricity.

The simplest instruments for measuring electro-motive force and current are based on the galvanometer. If the coil surrounding the magnetic needle consists of very thin wire it will have a high resistance and only a very small current will pass. When such an instrument is connected across the main wires leading from a dynamo as in Fig. 27

[1] The term 'quantity' of electricity will acquire a clearer meaning after reading Chapter XX.

the electro-motive force acting on the coil will be the same as in the main wires but the current will only be a very small fraction of the main current. The deflection then will vary with the electro-motive force and

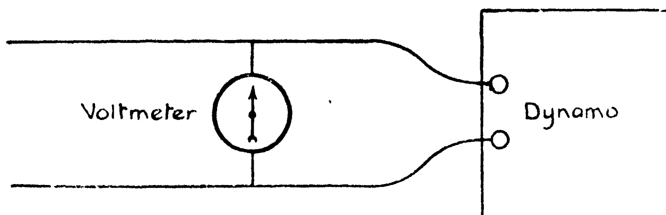


Figure 27. Diagram showing method of connecting up a voltmeter

the voltage indicated by the movements of the needle. Such an instrument is called a voltmeter.

An ampere-meter, or ammeter as it is generally called, may consist of a galvanometer with a coil of very thick wire connected in series as in Fig. 28. The electro-motive force is due to a fall of potential round the circuit. (If water instead of electricity were being considered the force tending to make water move from one point to another would be

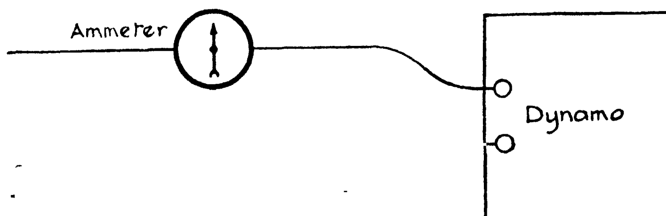


Figure 28. Diagram showing method of connecting up an ammeter

to a difference of level.) The fall of potential depends upon the resistance, and with a low-resistance galvanometer will be very small. It will not absorb more than a fraction of the power in the circuit, but since all the current passes through it and the potential difference between its terminals will be very small its indications will vary with the strength of the current.

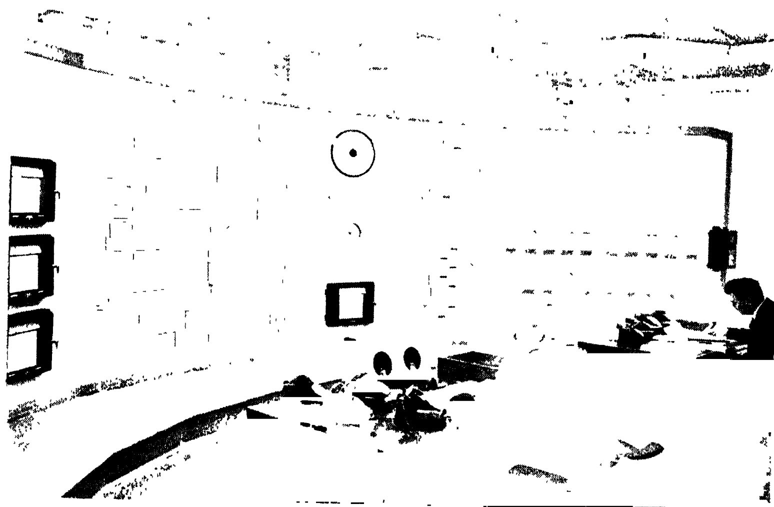
Other instruments depend upon the heating effect of a current, which is proportional to I^2R. If the resistance of a wire is practically the same for all temperatures, the amount of heat produced by a momentary current in it will depend only on the square of its strength. The heated wire will expand and, as the slack is taken up by a spring, will turn a pointer.

The total power, however, depends upon the voltage and the current strength, and an instrument for measuring the product of these is called a wattmeter. Space will only allow a brief statement of the principle upon which such an instrument is constructed. If a coil of wire suspended in a magnetic field carries a current it tends to set itself at right angles to the lines of force. This effect in a coil of high resistance will be proportional to the electro-motive force, and in a coil of low resistance to the strength of the current, so that the combined effect of two such coils (no iron being present) will measure the watts. If one is fixed and the other free to move, the motion of the latter will be a measure of the mutual attraction due to the current and the electro-motive force.

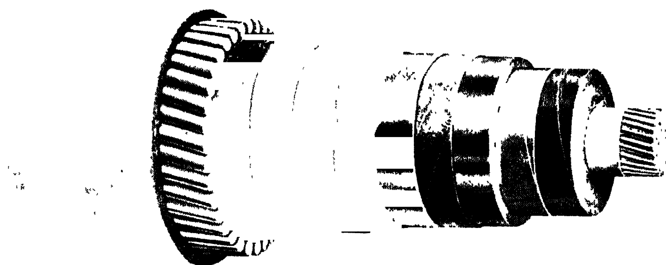
In generating stations the instruments record on rolls of paper the changes in the electro-motive force, strength of current, and power produced, so that very accurate calculations of the cost can be made. But this applies to the whole amount and, in order that each consumer shall be charged exactly for the quantity he uses, other instruments are required.

Behind the hall door or in some other out of the way corner of a house in which electricity is used for heating or lighting, is a small, compact instrument which the householder regards with a considerable amount of awe, not unmixed with suspicion. For it is upon the indications of this apparatus that his quarterly bill for current is calculated, and as the amount is small or large so he is prepared to look upon it as an upright judge or as a biassed advocate of the people who placed it there. The instrument consists of an iron case with a window in front and having a set of dials something like a gas-meter. The internal arrangements vary considerably in different types, and it may perhaps be sufficient to indicate the principle upon which one of these performs its duty.

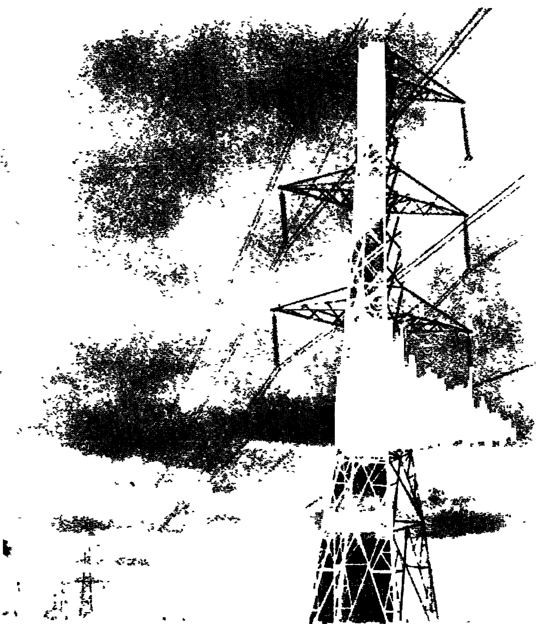
It should be noted at the outset that the pressure or 'voltage' of a public supply is constant, or nearly so; and as the quantity of electrical energy for which the consumer has to pay is measured by the product of the number of volts, the number of amperes, and the time, it is necessary to measure and record only the last two quantities. Suppose now a small electric motor is constructed so that at the voltage of supply a current of one ampere causes it to make one revolution per second, a current of two amperes two revolutions per second, and so on. Then the number of turns which the motor makes in any given time multiplied by the voltage of supply will give the total amount of electrical energy which has passed through it. Such a motor can easily be arranged to operate a set of dials so that readings are obtained directly in Board of Trade units of 1,000 watt-hours.



(*British Electricity Authority*)
XV*a*. A view of the National Control Room of the Grid. The dial in the centre gives the frequency of the Grid throughout the country



(*Callendar*)
XV*b*. 32 kW. 0·5 sq. in. gas-filled submarine cable of the type intended for the projected submarine power cable under the English Channel



(British Electricity Authority)

XVI*a*. Pylons, transmission lines and insulators of the 275,000-volt Super Grid



(English Electric Co.)

XVI*b*. 120 M-Va. 275–132 kV. auto-transformer, seen from the 132 kV. side

ELECTRO-MAGNETIC INDUCTION

The principles upon which nearly all methods for the production and application of electrical power depend were discovered by Michael Faraday between 1830 and 1832. He showed that if a magnet be moved so as to approach a coil of wire the coil has a current of electricity produced within it. If the magnet is withdrawn a current in the opposite direction to the first is produced. In fact any movement of the magnet such that the lines of force in its field cut the wire causes a current, the direction of which depends upon the direction in which the line moves. As a wire conveying a current has a magnetic field it is capable of acting on another wire in the same way, either by actually moving either wire, or by causing the strength of the current to alter so that the lines move inwards or outwards, and thus cut the second wire in their motion.

If the reader can keep these actions and reactions in his mind he will have no difficulty in understanding how nearly all the apparatus employed in the practical applications of electricity work. He must always picture a conductor conveying a current as surrounded by a field of magnetic force, and he may, as a rule, assume that iron is used merely to concentrate this force and to give it direction. If either wire carrying a current, or a piece of iron, is free to move, the movement will take place in such a way that the greatest possible number of lines of force pass through the iron. For example, a coil of wire through which a current of electricity is passing (Fig. 26) will 'suck-up' an iron rod until the latter protrudes equally at either end, and will exert considerable force in so doing. Two conductors carrying currents act upon one another by reason of the magnetic fields with which each is accompanied. And every electrical machine may be regarded as a magnetic machine in which the magnetism is produced by electric currents.

It is customary to express the strength of a magnetic field by the number of imaginary lines of force per square centimetre—measured at right angles to the direction of the force. Into the exact meaning of this it is not necessary to enter here, but it may be stated that the e.m.f. produced in a conductor is proportional to the number of lines cut per second; that is, to the strength of the field and the velocity with which the conductor moves. And as the movement of conductors in a magnetic field is the mèthod by which electricity is invariably generated for practical purposes, we may proceed to consider the construction and mode of working of generators, or dynamos as they are more usually called.

THE CONTINUOUS-CURRENT DYNAMO

Imagine a rectangle of wire to rotate between the poles of a magnet as in Fig. 29. As each side of the rectangle approaches the pole a current is induced in the direction shown by the arrows, and this increases until the centre of each pole is reached (when the greatest number of lines of force are cut per second), and then decreases until the rectangle has turned so that its plane is vertical. As the rotation continues, the side which at first passed the face of the south pole now passes the face of the north pole, and *vice versa*. The induced current now is in the opposite direction to that indicated by the arrows.

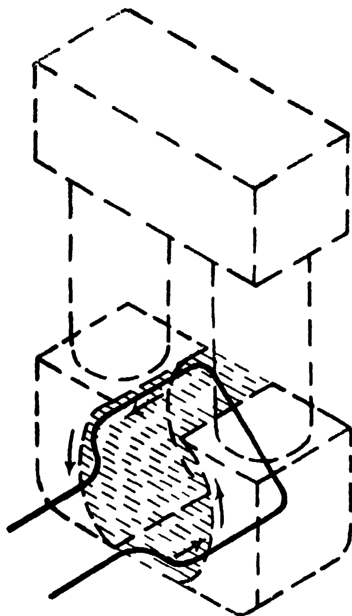


Figure 29. Rectangular coil rotating between poles of field magnets

A wire rectangle is too flimsy a thing to be rotated without some support, and a single coil can only cross the field twice in every revolution. So in the actual machine it is replaced by coils of similar shape, but of many turns, because each turn has a current induced in it, and the electro-motive force is proportional to the total length of wire cutting the magnetic field. In order to concentrate the magnetism of the poles in the gap between them, the rotating coil is mounted on an iron armature which, in the earlier machines, was of the form shown in Fig. 30. If each end of the wire is connected with a metal ring mounted on the shaft by means of a non-conducting disc, then the current can be drawn off as it is produced by brushes that make a sliding contact with the rings as in Fig. 31.

A continuous current is obtained by means of a commutator. This consists of a metal ring or cylinder mounted on an insulating drum, and cut in halves at opposite ends of a diameter, as in Fig. 32. Two brushes rest on this in such a position that when the current in the armature is just about to reverse the brushes change over from one half to the other, thus rectifying the alternation in the armature.

In this arrangement the coils are only cutting the lines of force for part of the revolution, and while the cheeks of the shuttle are passing

the pole-piece no electro-motive force is being produced. Modern armatures are made in the form of a drum, which is built up of a number of thin sheet-iron discs, threaded on the shaft. These are

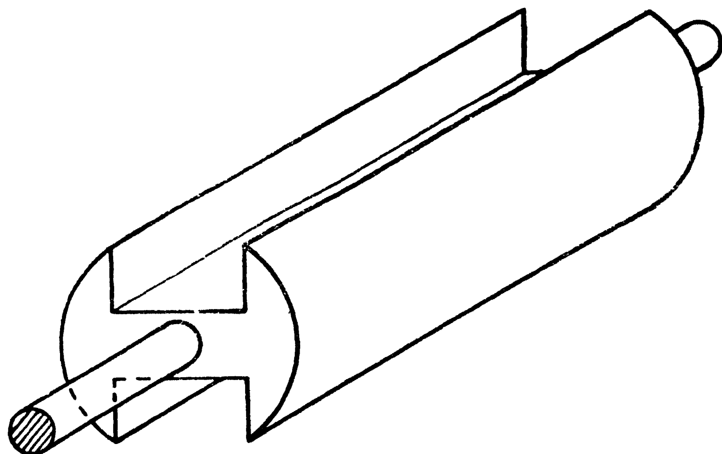


Figure 30. Siemens' H or 'shuttle' armature

separated from one another by coats of varnish or thin paper to prevent induced currents flowing through and heating them, and they are

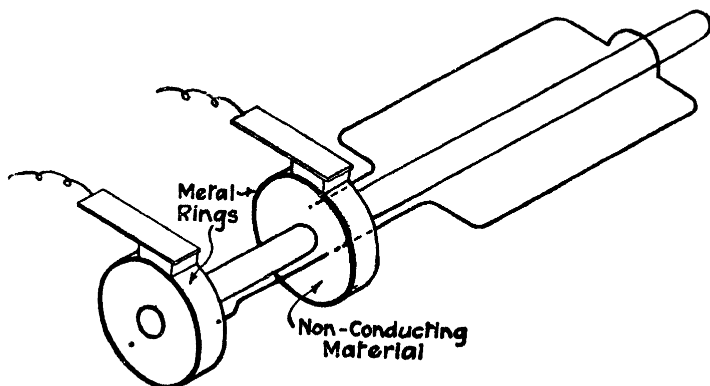


Figure 31. Slip rings

stamped with teeth in the edge to form slots in which the armature coils can lie. The coils are wound up separately and connected up with segments in the commutator. The latter consists of copper bars mounted

on a non-conducting sheath round the shaft, and separated from one another by strips of mica.

The brushes consist of carbon blocks held in a frame which can be rocked slightly backwards or forwards until there is the least sparking between the brushes and the commutator. The reason for this adjustment is as follows. The rotation of the iron armature causes distortion of the lines of force, so that instead of pursuing their usual path, they are dragged round slightly with the armature. If the brushes do not take off the current from each pair of commutator bars when the voltage is

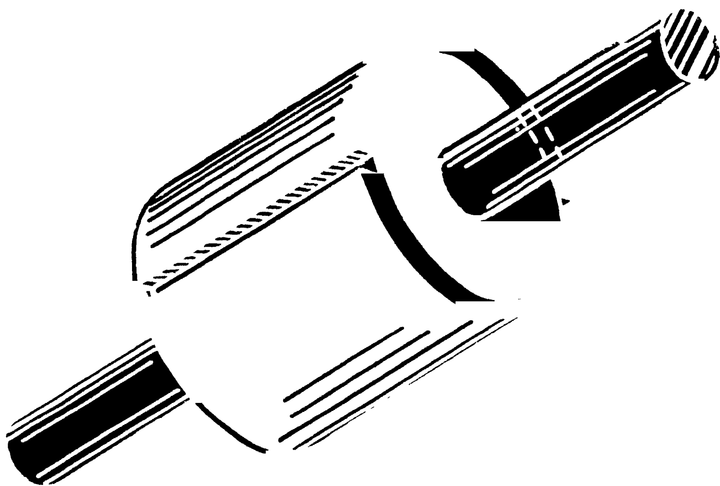


Figure 32. Two-part commutator

at its highest value, there is a tendency for the current to jump across to the brush before or after the bars have passed under it. And since the voltage is highest when the coil is passing through the strongest part of the field, the brushes which would normally be exactly opposite the pole pieces have to be given a 'lead' corresponding to the angle of distortion. In a modern machine their position is mid-way between the poles.

The magnetism in the field magnets is produced by the machine itself. Coils of wire are wound between the pole pieces, and these are connected up in one of the ways illustrated in Fig. 33. In the first method the current from the armature divides, part going into the outer circuit and part round the field magnets. If more current is taken in the outer circuit less goes into the field coils, the strength of the field is reduced, and the voltage of the machine falls. This is called shunt winding. In the other, or series wound machine, the same current flows round the

outer circuit as the field coils, and when the former increases the field strength increases and the dynamo rises to the occasion. Machines which have to bear varying loads have part of the winding in series and part in shunt, with such a proportion that each compensates the defects of the other. They are then said to be compound-wound.

The voltage of a dynamo depends upon the length of active wire in the armature, that across the ends being ineffective, and many turns of thin wire will produce a high voltage. It also depends upon the strength of the magnetic field. But a long length of thin wire has a high resistance

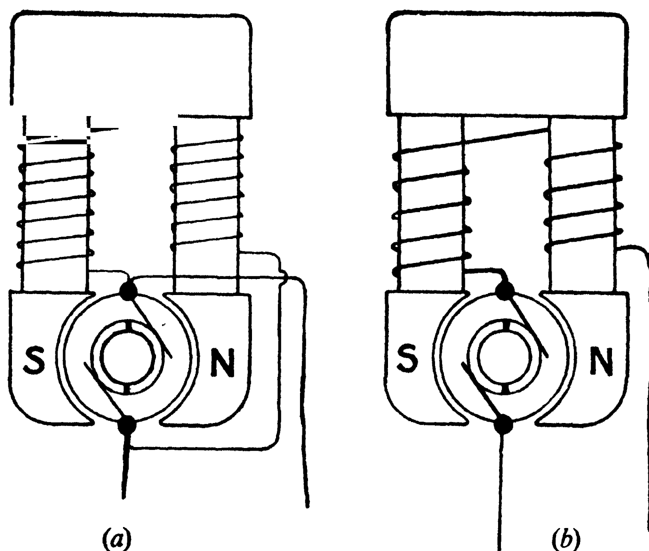


Fig. 33. Diagram showing method of winding dynamos: (*a*) shunt winding, (*b*) series winding

and the current from such an armature will be relatively weak. On the other hand, a few turns of thick wire will produce a current of low voltage but, as the resistance is also low, of considerable strength. The winding of the armature therefore determines the uses to which a machine can be put, though, as will appear later, the character of the current can be altered before use in any way that is desired with considerable ease.

Dynamos to give continuous or direct current, or D.C. machines as they are called, are not usually constructed to give a very high voltage owing to insulation difficulties. One way of avoiding these is by arranging dynamos on the following plan. Suppose there are three machines each giving 1,000 volts, and imagine them connected so that the first

terminal of the first dynamo is connected to the outer circuit, and the second to the first terminal of the second dynamo. The second terminal of this dynamo is connected to the first terminal of the third dynamo, and the second terminal of the third dynamo to the outer circuit. In this way the total electro-motive force becomes equal to the sum of the electro-motive forces of all three machines, or 3,000 volts.

The existence of only two poles which concentrate the lines of force in one direction leads to irregularities in the voltage which are very noticeable in lamps unless the machine is driven at very high speed; and as a high speed involves special difficulties in construction to secure exact balance, the avoidance of vibration, and a sufficient lubrication of the bearings, all modern machines except very small ones, or machines to be driven by turbines, are made with four or more poles. These multipolar machines have the field magnets in the form of a ring with magnet cores projecting from the inner surface, and the coils are so wound that the poles are alternately north and south. Instead of cutting the field between a single pair of magnet poles in each revolution, the armature coils cut the field between two, three, or more pairs, and the successive impulses of electro-motive force occur more frequently. A lower speed is therefore possible, and the lamps do not flicker.

A word of explanation is perhaps necessary in regard to the 'interpoles'—the small field magnets between each pair of main poles. These are so wound as to act in opposition to the pole behind, and thus to convert the gradual change of e.m.f. in the armature coils into a rather sudden one. In the absence of interpoles, which are fitted on most machines nowadays, the effect of a pole on an armature coil persists during the period when the armature coil is leaving the pole and when the corresponding commutator bars are leaving the brushes, and a certain amount of sparking occurs, which not only increases the wear of the commutator and brushes, but also causes loss of energy. With interpoles both these faults are avoided.

THE ALTERNATING CURRENT DYNAMO

It has already been remarked that a dynamo or generator provided with slip rings instead of a commutator gives an alternating current, and for small machines this is the main constructional difference between them. Moreover, in machines giving continuous current in one direction it is obviously necessary that the commutator and the armature should rotate in order that the change of direction in the armature coils may be rectified. But if an alternating current is required the condition for its production is merely that conductors and lines of force should continually cut one another and this can be secured as easily by rotating the field magnets as by rotating the armature. In very large machines

there is clearly an advantage in rotating the field magnets rather than the armature, because it is the armature which carries the main current; and when heavy currents at high pressure have to be taken from rings there is bound to be some loss owing to the imperfection of sliding contacts. On the other hand, a comparatively small low-tension continuous current is necessary to excite the field-magnets, and is conveyed through slip rings without any appreciable disadvantage. The current from the armature is then collected by cables attached to the fixed armature coils.

A modern alternating current generator consists of a rotating wheel, called a rotor, carrying on its rim a number of pole pieces, surrounded by coils of wire, which must be fed either with direct current from a separate dynamo, or from one mounted on the same shaft. Surrounding the rotor is a large ring-shaped frame, having coils fixed on its inner surface. The poles on the rotor are alternately north and south, and as it rotates the lines of force between successive poles cut the coils of the fixed armature or stator. For each pair of poles in the rotor passing the armature coils per second, there will be a complete alternation of the current, so that the periodicity or frequency will be given by the product of the number of pairs of poles and the number of revolutions per second. Thus suppose there are sixty poles and a corresponding number of coils, then at 1,200 revolutions per minute, or twenty per second, there will be 30×20 or 600 alternations per second.

The example just given assumes that the wire in the stator is wound continuously round successive poles, giving what is known as a single-phase current. If, however, the wire is in two portions wound round alternate poles, the current will be a maximum in one when it is at a minimum in the other, a condition known as 2-phase. More frequently there are three sets of stator coils, giving a 3-phase current.

It will, perhaps, be interesting to notice the elaborate precautions which are taken in the winding of modern electrical machinery. The strip copper is wound on a model or 'former' so as to be of the exact shape it will take in the machine. It is then cleaned and dried, the free ends wrapped with superfine linen tape, twice dipped in special varnish, and baked between each process. The portion which is to lie in the slot is then insulated with mica, parchment paper, and linen tape, dried in a vacuum, impregnated with oil and acid-resisting varnish, and baked for twelve hours. The slots are lined with leatheroid troughs to prevent abrasion. For peripheral speeds of more than 6,000 ft. per minute steel wire binding is insufficient, and the conductors are held in place by hard-wood wedges driven into dove-tails formed in the outer portion of the slots. The finished armature is baked for twelve hours and given a final spraying of air-drying, black varnish. It may be left to the reader to imagine the vast amount of patient investigation and experience

which lie at the back of such a series of processes; and these are quite apart from those concerned with the mechanical (as distinct from the electrical) features of a modern armature.

TRANSMISSION AND DISTRIBUTION

The size of the wire required to transmit electricity over a distance is determined by the resistance. This is proportional to the product of the resistance of the wire and the square of the current strength. On account of its high conductivity copper has been very widely used for the purpose, though aluminium is also used on account of its lightness. Its conductivity is less than that of copper, but volume for volume its weight is less than one-third.

As the power transmitted in a given time is measured by the product of the voltage and current, for large quantities either the voltage or the current, or both, must be high. But if the strength of the current is doubled, the losses due to resistance are multiplied by four, so it is usual to employ high voltages in transmission wherever possible in order to save the cost of copper. The determination of size, however, is not arbitrary, and several factors have to be taken into account.

While high voltages are desirable for transmission they are not always suitable for actual use, and one of the contrivances which adds so much to the adaptability of electrical power is the transformer. This consists of two separate coils of wire wound on a soft-iron core. When a current of electricity in one starts or increases in strength a current is produced in the *opposite* direction in the other. Similarly when the current in the one decreases in strength or stops a current is produced in the *same* direction in the other. As the 'induced' currents in the second coil depend upon the number of lines of force cut by each wire per second, and the number of wires, the voltage depends upon the number of turns. And, since the power in the two coils is practically the same, it is possible to 'step-up' from a current of low voltage and relatively great strength to one of high voltage and small strength, or *vice versa*. The ordinary Rhumkorf or induction coil is a step-up transformer, and the coils used for converting the high-tension current from long-distance transmission lines to low-tension current for tramways and other purposes are step-down transformers. Both the entering and leaving, or primary and secondary, currents are alternating. The change from alternating to direct is effected by a motor generator, to be described later.

The transmission of electricity at high voltage necessitates special precautions, for not only is the tendency to leakage immeasurably greater, but a shock is highly dangerous. Consequently, a common practice is to generate electricity at 11,000 volts, transform up to 33,000 volts for

transmission, and then transform down to 200–250 volts for supply. In the grid or network of distribution in Great Britain, the voltage is raised to 132,000 for transmission. This change has led to an enormous development in transformers and high-tension switches.

In order to economize copper most electric light stations distribute electricity by means of what is known as the three-wire system. Suppose there are two dynamos connected up as shown diagrammatically in Fig. 34. If each dynamo is capable of producing current at 230 volts, the total electro-motive force in the two outer wires will be 460 volts.

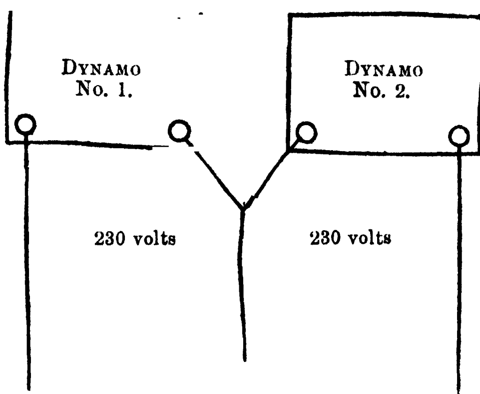


Fig. 34. Diagram to illustrate three-wire system

The wires leading into the premises of each consumer, however, are always the inner and one outer, so that the electromotive force inside the dwelling is only 230. If for power, 460 volts is used, and the fittings must be of a special character.

If electricity has to be distributed across country over long distances, then there is an advantage in using high-tension currents.

In California, the Pacific Light and Power Corporation erected two hydroelectric stations, about four miles apart, at Big Creek, seventy miles from Fresno. From there power was conducted to Los Angeles, 275 miles away, at a pressure of 150,000 volts, where in addition to domestic and factory use it served also the Pacific Electric and Los Angeles railway systems. When it was built, this installation not only had the highest voltage which had ever been employed on a commercial scale, but it transmitted also over the longest distance which heavy currents of electricity had yet been conveyed either overhead or underground. Today, however, heavy currents are being transmitted at 220,000 volts, and lines at over 400,000 volts are projected.

The employment of such enormous pressures has been rendered

possible only by improvements in the designs and construction of switches and transformers, see Plate XVI*b*. When a circuit conveying a high-tension current is broken, the electricity tends to jump across, and the resistance that it encounters causes an 'arc', which may fuse the metal of which the switch is composed.

An 'arc' or tongue of flame, formed by the current jumping a gap, is flexible, and is deflected by a magnet just in the same way that a flexible wire carrying a current would move so that its magnetic field corresponded to the one acting upon it. Switches are, therefore, often provided with magnets which prevent the arc becoming established by blowing it out as soon as it is formed. And all switches, whether for direct or alternating current, are operated partly by springs which cause the contact to be broken with extreme rapidity.

The switches used for very high tension are immersed in oil which has a high insulating power, and are never operated directly by hand. They are opened and closed by electro-magnets, and the small switches which control them have only to deal with a weak, low-tension current entirely independent of the main circuit. The high-tension switches were at first locked up out of sight and touch in a brick or concrete chamber, which was opened only for the purpose of occasional inspection and repairs. The more recent tendency is to have these switches out of doors.

MOTORS

The reader who understands the D.C. dynamo will have no difficulty in understanding the D.C. motor, for they are in all essential parts the same, and one machine can be used for either purpose. The magnetic effect of the coils on the field magnets and armature is concentrated between the pole pieces in such a way that when a current is sent through the machine attraction occurs between armature and field magnet, and the former turns. But as soon as the poles between which the attractive force is exerted come opposite to one another, the commutator arrives at a position in which the current is reversed. The armature pole is now of opposite polarity, and repulsion ensues. This is repeated for every pair of poles, and a continuous rotation of the armature is secured.

Like the dynamo, the D.C. motor may be shunt, series, or compound wound. The shunt motor develops very little power at low speeds with heavy loads, because most of the current goes into the armature and the magnetic field of the field magnets is therefore weak. As the armature rotates, however, it behaves as in a dynamo, and produces a back electric-motive force in its coils which is equivalent to a resistance, and drives more current round the field magnets. Such a machine is largely self-regulating.

In a series motor the same current passes round the armature and field magnets, and from the moment it is switched on there is a strong turning movement. This makes the series machine valuable for cases where large power at low speed is required, as in trams, lifts, and cranes, which have frequently to be stopped and restarted. Constancy of speed under varying loads is secured by compound winding, in which the defect of each system is compensated by the other.

As the resistance of the armature coils is invariably lower than that of the field magnets, the greater proportion of the current tends to pass through them when the motor is at rest, and it is not until the machine has acquired some speed that the back voltage in the armature reduces this to a safe amount. In order to prevent the armature coils becoming overheated and 'burnt out' all D.C. and some types of A.C. motors are provided with starters. These are boxes of resistance coils fitted with a switch which, as it is turned, causes the current to pass first through the whole length of resistance, then smaller parts of it in succession until the whole of the resistance is cut out and the current passes directly to the motor. The type of starter used on tramways will be described in Chapter XIV.

The problem of obtaining motion from an alternating current is a much more difficult one, but has been solved in three ways. If an alternating current is passed through the armature of an alternating current dynamo at rest the machine will not start, for the tendency to rotation in one half is balanced by the tendency in the other half. And even if the armature is rotating, the two opposite tendencies may be equal. But if the speed is such that each coil passes from one pole to another during half an alternation of the driving current, then the direction of the latter will be changed just in time to convert what would have been a repulsion into an attraction, and the machine will continue in motion at constant speed. Thus if the frequency is 100 per second, there will be 1,200 half-alternations per minute, and if there are four pairs of poles the speed must be $\frac{12{,}000}{8} = 1{,}500$ r.p.m. Such a machine is called a synchronous motor, and so long as it is not overloaded it will continue to run at constant speed.

The second type is called an induction motor. Suppose there are two or three sets of coils in pairs in the stator, and suppose them to be fed with 2-phase or 3-phase current, so that the maximum magnetic effect is produced successively all round the ring. Any conductor, such as a copper bar, will follow the coils as each one is successively excited, because of its tendency to move to the strongest part of the field. The rotor consists, therefore, of a number of copper bars, each end of which is fixed to a copper ring, forming a sort of squirrel cage from which this

type of rotor takes its name. If the initial load is not high, this motor is self-starting, and as no current passes into the armature conductors no slip rings are required. If such a motor is required to deal with heavy initial loads, the coils are wound on the rotor and current is led into them by means of slip rings and carbon brushes. When the machine is fairly started the brushes may be lifted from the rings.

The third type of motor is used for railway work, and takes single-phase current. It is similar in principle to the direct-current machine, but whereas in that case the commutator reverses the direction of the current in the armature, in this case the reversal takes place by the alternating current in the field magnets. The armature coils are short-circuited by connecting opposite brushes in pairs, and the brushes are fixed so that each set of coils is closed at the time when the field-magnet poles exert the most powerful turning effect. This possesses all the merits of the D.C. series machine, with the additional advantage that the current to work it can be conveyed cheaply over great distances by relatively thin wires.

We are now in a position to understand how an alternating current is converted into a direct one. If the current is sent through the armature of a synchronous motor, entering by slip rings, the machine will, as has been observed, rotate at constant speed. If, moreover, the armature-shaft be fitted with a commutator to which the other ends of the coils are attached, the armature will turn at the correct rate to enable the commutator to deliver to the brushes a direct current. A Rotary Converter of this kind usually has fitted on the same shaft a small induction motor, which serves to start it and run it up until it is in step with the alternating current which drives it. The field magnets are fed by current from the D.C. end of the machine.

ELECTRICAL STORAGE

The value of electrical power is enormously increased by the fact that it can be stored. This is accomplished in cells which are distinguished from those used in the generation of electricity on a small scale for electric bells, telephones, and experimental work, by being called storage cells, or secondary cells, or more generally accumulators. A number of cells constitutes a battery. The battery can be fixed up permanently, or enclosed in a box, taken to a generating station, charged, and then taken away to the place where the electricity is to be used. This is just as simple as taking a piece of clockwork to be wound up and then removing it to another place to drive machines.

There are, broadly speaking, three types of secondary cells in use, two of which are very similar, and depend upon a discovery made by Planté more than seventy years ago. He found that when a current of

electricity was passed for some time through a cell containing two lead plates immersed in dilute sulphuric acid a current could afterwards be obtained in the reverse direction. At first, not a great deal of the electricity could be stored in this way, but by repeatedly charging and discharging the cells, the plates became capable of taking up and retaining, as it were, a greater quantity. The total amount of electricity put into the cell can in no case be recovered, and under ordinary conditions there is a 20 per cent or 30 per cent loss. The storage is due to a somewhat complicated chemical change, or rather series of changes, in which one of the plates is converted into lead peroxide, PbO_2, a chocolate-coloured substance. The immersion of the plates in the acid may be assumed to lead to a thin layer of lead sulphate, $PbSO_4$, being formed on both plates. The passage of the current causes the separation of hydrogen at the negative plate, and this reduces the lead sulphate to lead, which it leaves in a spongy condition. At the other plate, an oxidizing action occurs, and the lead plate is oxidized to the chocolate peroxide. The liquid in the cell becomes denser, showing the presence of more sulphuric acid than before the passage of the current.

The tendency for the spongy lead to be oxidized and the peroxide to be reduced causes a current to flow in the opposite direction to the charging current when the plates are connected to an external circuit. The e.m.f. is always about 2 volts—or 2·2 volts for a fully charged cell, falling a little as the cell is discharged. With lead plates the active materials are at first produced only in a thin surface layer, but repeated charging and discharging increases the depth and enables the duration of charge and discharge to be increased. The process, however, is very tedious, and the active material is liable to break off in flakes from the surface of a flat plate.

An improvement was effected by Faure, who employed an alloy of lead and antimony cast in the form of a grid and pressed into the interstices of the grid a paste of red lead, Pb_3O_4, and sulphuric acid. This secured at once a greater amount of active material, and reduced the time required for 'forming' the plates. Numerous other modifications have been introduced in order to secure a greater sponginess throughout, so that chemical action can proceed more readily and affect a great quantity of material. Thus, while the percentage occupied by the pores in an early type of Planté plate was only 25, that of a modern chloride cell reaches 60 or 70.

It will, perhaps, be not without interest to indicate one way in which this has been achieved. The Chloride Company make their positive plates in the shape of perforated slabs with spiral rosettes of thin lead strip pressed into the holes. These are 'formed' by the original Planté process. The negative plates contain pellets of a fused mixture of lead and zinc chlorides in the perforations. On passing a current of electricity

through these plates in the cell, the zinc is removed, and the lead is reduced to the spongy condition.

Lead accumulators require a great deal of care in management. They must not be charged or discharged too rapidly, or the active materials tend to become displaced. The amount of liquid necessary, and the use of the heavy metal lead, renders them of great weight. The corrosive character of the acid requires the cells to be made of glass, ebonite, or, for very small ones, celluloid. But the many attempts which have been made to discover a lighter metal that would serve the purpose, and a method of construction that would withstand hard usage, have resulted in a single success which may now be described.

The Edison accumulator was invented about 1904, and though it made slow progress at first, improvements in manufacture have secured for it during recent years a considerable reputation. Edison employed iron and nickel instead of lead, and a solution of caustic potash instead of sulphuric acid. The construction of the plates involves a degree of mechanical ingenuity thoroughly in keeping with the standard of the twentieth century. The positive plate consists of a nest of nickel-steel tubes, each one of which is formed by a perforated nickel-steel strip wound in spiral. These are packed tightly within alternate layers of nickel oxide and flakes of metallic nickel. Plate XIV*b* illustrates the single tube and a complete plate. The negative plate is also of steel and contains oxide of iron pressed into a number of lozenge-shaped pockets. The liquid and the immersed plates are contained in a closed-ribbed nickel-steel box. The cell contains water with 21 per cent of caustic potash, and the solution requires a little water occasionally. The chemical changes which take place have not been fully worked out, but the net effect is supposed to be that the oxygen of the nickel oxide is transferred to the iron plate, rendering that more highly oxidized. But ordinary chemical analysis reveals no difference in the composition of either plate charged or uncharged.

The ability of this cell to withstand hard wear may be gauged by the fact that some were tested by being lifted and dropped 2,000,000 times, the process being continued for twenty-two days and nights, without any mechanical defect arising, and with a loss of only one-quarter per cent in efficiency. On one occasion a fire in a garage boiled out all the liquid, and yet, when filled, the battery is said to have been as good as ever. Moreover, the Company quote cases in which cells in regular practice are charged for short periods at five times the normal rate—a proceeding that would, in lead accumulators, cause buckling of the plates and displacement of the active material.

The e.m.f. is only about 1·2 volts, so that more cells are required for a given voltage than in the case of ordinary storage batteries.

Accumulators are used very frequently in electrical power stations

for dealing with variations of load, charging being accomplished when very little current is required in the mains. They are also used to a limited extent for traction. Small portable types are used to a large extent in displacement of primary batteries—for miners', policemen's, and domestic lamps, for radio receivers, for surgical and medical and dental work, for motor-cars, submarines, railway and other signalling, for electric clocks, and for a score of other purposes.

Wherever there is a cheap source of power such as water, or easily mined coal, or a plentiful supply of oil, and, very soon, where there is a supply of atomic energy, there electricity can be generated and distributed in thousands of horse-power along a web of overhead or underground wires, which can be tapped at any point in their length and used to drive machines silently, effectively, and overcome all obstacles. Already, as we know, it illuminates the night, drives mills and factories, trams, and steamships, coats baser metals with copper, nickel, silver, and gold, makes the blocks by which many of the illustrations in this book are produced, manufactures some of the nitrogen compounds upon which the wheat supply of the world will ultimately depend, and in the Kjellin furnace excites the particles of cold steel until they glow and flow like water.

THE BRITISH GRID SYSTEM

The first appreciable demand for electricity was created by the development of the carbon filament electric lamp in the late 1870's. The first British public measure dealing with electricity supply was the Electric Lighting Act of 1882. According to this, licences could be granted to any local authority, company or person to supply electricity. The conditions under which this could be done were, however, defined in such a way as to give little encouragement to large-scale enterprise. A large number of small independent power stations were gradually set up, engaged almost entirely in supplying electric light systems in heavily populated areas. No attempt was made to secure uniformity, and there were prohibitions against association and combination of certain types of undertaking.

For various reasons, and especially because there was no obligation on the distribution undertakings to take supplies of electricity in bulk, large-scale generation and distribution of electricity had not become effective in Britain before the First World War.

The outbreak of that war, with the imperative demand for a better supply of electricity for the making of armaments, exposed the weaknesses of the existing system, in its inability to supply enough electricity, with a flexible distribution, and at an economic cost. A committee to consider these problems was set up in 1918. An Electricity Commission

was set up in 1919, to promote these aims by voluntary agreement. It succeeded in securing much expert technical analysis of the problems but was unable to take effective action, as it lacked compulsory powers. In 1925 another committee was formed, to report on the policy which should be followed in order to ensure an efficient and effective supply of electricity to the nation. The committee found that there were no fewer than 572 separate supply undertakings, deriving their electricity from 438 power stations. They recommended the establishment of a national system of transmission lines. This became known as the Grid. Its function was to interconnect selected power stations, and distribute electricity wholesale from the most efficient stations. The committee recommended that, together with the Grid, there should be a standardization of equipment and fittings.

The Central Electricity Board was set up in 1926 to carry out these recommendations. The construction of the Grid, as initially planned, took six years, and cost £26,700,000. When the Second World War broke out in 1939, the initial plan was complete. Sir Johnstone Wright, the president of the Institution of Electrical Engineers, said in that year that the state of organization on the generation side of British electricity production was without a parallel in any other country.

The loss of capacity due to bombing during the war was from about 2 per cent to 4 per cent for the whole system. The flexibility of the network and the ability of one part to support others in emergency were found to be very great. The restoration after attack was unexpectedly quick. At Coventry, for example, on the day after the attack, the load fell to 20 per cent of its normal value. Within four days it had recovered to 32 per cent, and in three weeks to 85 per cent. Among the measures that contributed to this was the establishment of a national pool of reserve equipment stored at safe places all over the country. In the period of 1936–9, much thought had been given to planning the operation of the Grid under war conditions and attack, and in the event these proved very successful.

By 1946, with extensions, the expenditure on the Grid had risen to £40,000,000.

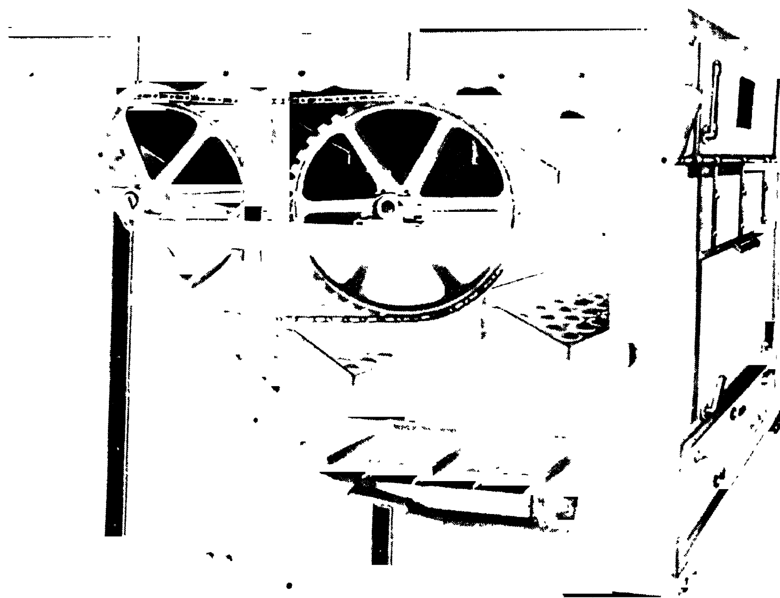
In the initial six years' construction, 150,000 tons of steel were used, mostly for 28,000 transmission towers, covering the country from the Grampians to the South Coast, and from East Anglia to Land's End. About 12,000 tons of aluminium were used in the lines for carrying the high voltage electricity, supported by 200,000 porcelain insulators. With the subsequent extension of the Grid, these figures have been much increased. Sixty rivers were crossed, including the Thames at Dagenham. The towers for supporting the conductors are 487 ft. high and weigh 290 tons each. The span is 3,060 ft.

The equipping of the Grid stimulated the design of transformers and



(G.E.C.)

XVIIa. The components of filament lamps are assembled on the machine on the left and pass to the support and filament mounting machine (*left foreground*) after lamps have been exhausted and filled with gas (*right foreground*). They are capped on the finishing machine (*right centre*), inspected and packed



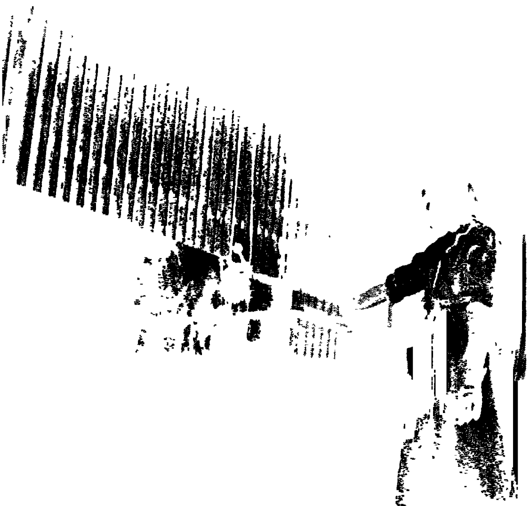
(*Metropolitan-Vickers*)

XVIIb. An electric baking oven: showing internal arrangement



(G E C)

XVIII*a*. Coating a fluorescent tube. A thin cream of fluorescent powder is blown up the tube and then the solvent is evaporated



(G E C).

XVIII*b*. Air, gas and vapour are evacuated from the tube, and some mercury and argon introduced

switchgear, metering apparatus, protective gear against lightning flashes and many other developments.

Two 75,000 kVA transformers were installed at Liverpool, each weighing 147 tons. The 100,000 kW. turbo-alternators at the Battersea Power Station have stators weighing 148 tons, and rotors weighing 82 tons.

At the end of 1946 the Grid contained 5,161 miles of transmission lines, 3,675 operating at 132,000 volts. There were 348 switching and transforming stations, with an aggregate capacity of handling 13,920,200 kVA. The Northfleet switching station was the largest in area and number of switches, operating at 132,000 volts.

At this date, the Grid contained 142 selected power stations, with an installed capacity of 11,588,306 kW. When the Board was set up, the average size of generation was 10,000 kW. The average size of new ones had by 1946 been raised to 40,000 kW.

The Board started an immense project of standardization. A frequency of 50 cycles per second was set as the national standard. In the course of a number of years, 903,000 kW. of generating plant, 354,000 kW. of converting plant, and 1,840,000 h.p. of electric motors in the premises of 235,000 consumers were changed to the new standards, whose supplies had to be maintained during the process.

In 1926, the public supply of electricity was 7,000 million units a year from more than 500 generating plants, in 1946 it was 41,240 million units, 99·3 per cent of which was produced by 190 stations. Before the outbreak of war, production was concentrated in the most efficient stations, and old and inefficient plant kept in reserve for meeting peak loads and breakdowns.

The efficiency of the Grid as a whole depended on unified control. Accordingly, the network was organized in seven national regions, these being controlled from one national centre in London. Apparatus in the control room automatically recorded what was happening in the provincial stations, the loads being carried, whether switches were open or closed, etc. The circuits bringing this information could also be used for telephonic and telegraphic communication. In the control centre, teleprinters in communication with the main centres enabled the engineer-in-charge to send instructions to each centre, in the light of the general situation. Some 6,200 circuit miles of communication channels were rented from the Post Office's lines for these purposes, and 80 per cent of them were underground.

The introduction of the Grid led to great economies in reserve plant. Instead of every independent plant having its own reserves, which represent idle capital when not running, a few reserves could be made to serve a much larger number of stations. The plant released from reserve could then be used to add to the normal output. It was estimated that by

the end of 1946, the capital saving from this cause was already equal to the whole of £40,000,000 spent on the Grid to that date.

The second major economy was in the consumption of fuel. In 1946 the price of coal was 194 per cent above the 1932 level, but the average cost of generation per unit of electricity had increased by only 32 per cent, and the average fuel consumption per unit sent out had decreased by 16 per cent. Calculations showed that the downward trend in production cost of electricity due exclusively to Grid economies was about 17 per cent in the period between 1932 and 1938.

When the war began, the complete blackout of external lighting shifted the time of peak demands from the late afternoons of the winter months to about 9 o'clock in the mornings. The mass evacuation took a certain amount of consumption into the countryside. There was a vast increase in electrical demand for the armament industries. Many factories were built in, or transferred to, the country. Shipyards, barracks, aerodromes, searchlight stations, etc., needed supplies. In some cases, large new factories needed as much as 50,000 kW. from the Grid. In 1941 and 1942, 500 miles of extra transmission lines were built to meet these needs.

Under war conditions, all reserve generating plants were kept continuously turning over, so that in an emergency they could be immediately run at full power, to pick up load.

From the beginning of the war, the Grid was operated as a unit. The central control was at the Bankside Generating Station in London.

This was heavily damaged in a raid, so the National Control Organization was transferred to a disused underground station near St. Paul's. Throughout the remainder of the war, the control engineers directed the operations of the generating stations and the Grid from this bomb-proof shelter.

When the war was over, plans for extending the Grid system at a cost of £200,000,000 were proposed. It was aimed to have 6,000,000 kW. of new plant in the selected stations by the winter of 1950.

Owing to the war the manufacture of generating plant had been restricted, and extensions of plants had accordingly been curtailed. Already at the end of 1944, load-shedding had become necessary on two occasions to prevent a widespread disturbance of the system. By 1946, load-shedding up to five hours had become necessary on fifty-four occasions.

The problem of distribution is greatly complicated by the variation in demand. This is shown on three typical days in Fig. 35.

The sharpness of the peaks between 8–9.30 a.m. and 4–5.30 p.m. on Mondays to Fridays, shows how large a reserve of power plants is necessary to meet the demand without inconvenience. The rearmament programme has prevented the completion of the plant extensions

originally planned. Consequently, it has been necessary to organize load-spreading. Day shifts in factories have been staggered, day shifts transferred to night shifts, and the transference to night-working of

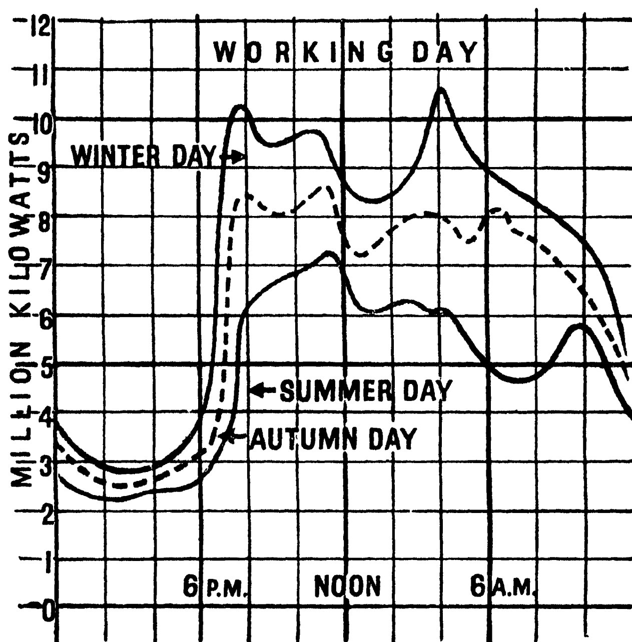


Figure 35. Demand curve of power required from the National Grid on three separate days

processes consuming much electricity, but not requiring many workers. But when the demand, in spite of such arrangements, exceeds the supply, the plant can only be protected from overloading by load-shedding.

Every contribution towards reduction of demand, especially at the peak hours, is therefore very helpful. In this housewives can make a most useful contribution by minimizing the amount of electric heating and cooking at the hours of 8–9.30 a.m., and 4–5.30 p.m.

Immediately after the war there was a serious loss of efficiency owing to a decline in the quality of coal. It was calculated that there was a loss of 380,000 kW. owing to boilers not giving their full capacity for this reason.

The increase of production of electricity by six times in the period 1926–46 has led to widespread transference of factories from old industrial centres to more attractive and healthy sites, and to the introduction

of newer factories and more varied industries in the old centres. It has quickened and raised the standard of life in the rural areas.

Even very big firms, consuming much electricity, such as Messrs. Lever Brothers of Port Sunlight and Messrs. J. & P. Coats of Paisley, have found it cheaper to buy electricity from the Grid, than to make their own.

The expansion in electricity supply has led to the extension of its use in transport. The whole of the suburban system of the Southern Region of British Railways has been electrified, and, including underground systems, over 1,000 miles of railway had been electrified by 1946.

The great success of the Grid led to the establishment of the British Electricity Authority in April 1948, to conduct the complete organization of the electricity supply industry for the nation. The English section of the Authority works through fourteen Area Electricity Boards, which own and operate the local industry.

In the year ending 31st March 1951 the Authority generated 55,000 million units of electricity, 13·1 per cent more than in the previous year. It had 289 power stations, with plant rated at 14,592,303 kW. and output of 13,156,000 kW. During the previous year, 918,000 kW. of new plant had been installed. Forty-three new power stations and 31 large extensions were in construction or planned for completion by 1956.

The Authority was the largest purchaser of coal in Britain at about 32½ million tons. It had a labour force of about 155,000, including 12,500 technical engineering staff, and 35,000 in administration. The main transmission lines were then 4,506 miles long. The construction of 265 miles of 132,000 volt lines, and 371 miles of Super Grid at 275,000 volts, was begun.

The number of consumers grew to over 13,000,000, and the price of electricity fell from 1·200*d.* in the previous year to 1·181*d.*

Eight new power stations had been brought into service since 1948, and three of these in the past year: Croydon B, Agecroft and Poole.

The Croydon B plant will ultimately produce 315,000 kW., with six 52,500 kW. turbo-alternators and 12 pulverized fuel fired boilers, each capable of raising 320,000 lb. of steam per hour. The construction of the foundations of this plant involved the excavation of 297,000 cubic yards of earth; 8½ million bricks were used and more than 10,000 tons of steel.

The Agecroft High Pressure plant at Salford will ultimately produce 210,000 kW. It has two 300-ft. cooling towers, and a chimney 365 ft. high. When work on the foundations was begun, a large fissure was found in the rocks beneath the surface, containing much water. This water has been turned to use for cooling tower make-up.

Poole Power Station will have an ultimate capacity of 200,000 kW., consisting of four 50,000 kW. sets. The station is built on mudland reclaimed from the harbour. Its foundations consist of an enormous solid concrete block weighing about 150,000 tons. This provides a secure base for the turbines and boilers.

The Authority operates 39 collier ships varying in size from 1,500 to 4,000 tons for the transport of coal. These bring about four million tons of coal a year to the power stations.

Since 1948, the Authority has brought electricity to 28,426 farms, bringing the total to 109,000. It provides an advisory service on the utilization of electricity for crop drying, soil warming, glasshouse heating and dairy sterilization. It has conducted research on soil sterilization and milk cooling.

One hundred and thirty of the Authority's plants consist of old, small installations of less than 10,000 kW. These are old, wasteful and expensive, but cannot yet be replaced because of shortage of plant. In spite of the continued use of this old plant, the efficiency for the system as a whole continues to rise, owing to the highly efficient big new stations coming into service. The overall thermal efficiency in 1950–1 was 21·54 per cent, compared with 21·15 in 1948–9.

Though the increase in output capacity in 1950, 965,000 kW., was larger than in any previous year, the shortage experienced was greater than in the previous twelve months. This was due to the great rise in demand.

The new 'Super Grid', being built to operate at 275,000 volts, will enable bulk supplies of electricity to be transmitted from new plants being built in the East Midland coalfields, to London and other big towns. The East Midland coalfields are among those which the National Coal Board has scheduled for rapid development. By having the plants near the field, the effect of rising costs of coal transport will be avoided. The electrical losses through transmission over great distances will be minimized by using the very high voltage of 275,000 (Plate XVI*a*).

The first of the new power stations for the Super Grid is at Staythorpe near Newark, and is already in partial operation. It will send power at 275,000 volts to Sheffield, 41 miles distant. The contracts for 371 miles of Super Grid have been placed. When complete it will connect Sheffield and Glasgow, and Tilbury and Elstree.

The Authority has research laboratories at Leatherhead to investigate Super Grid and other problems.

Among the research activities in progress are studies of the pilot district-heating installation in Pimlico, London. The estate is supplied with central heating and hot water from low-pressure steam from the Battersea Power Station.

Another interesting research is on the attempt to adapt gas turbine

experience to design a prime mover on similar principles, but working with steam.

A contract has been placed for the installation of a big 100 kW. wind-power generator on a windy site in North Wales. It is expected that the plant will go into service in 1952. The British Isles are particularly windy, and the winds offer quite prodigious sources of power, if effective means of harnessing them can be worked out.

The great power stations, and the whole system, offer a multitude of interesting and important problems for research.

How is the whole great electrical system controlled in operation? This has been rationalized to a very high degree. It is carried out by one man from a small room in a National Control Centre in London (Plate XV*a*).

The control room in the old St. Paul's tube station is about 20 ft. in diameter, and lighted with fluorescent lamps. The control engineer (one of five who perform this duty in rotation) sits at a desk with a diagram of the whole system, probably the biggest unit of its kind in the world, watching frequency meters and other instruments. The frequency meter should register a steady cycle of 50 per second. If it falls appreciably below 50, it shows that plants must be failing to meet the demands on them. A severe change in weather can increase the demand by up to 20 per cent.

The load is forecast on the basis of reports from the areas on estimated industrial and domestic demand, as affected by meteorological conditions, and other factors. The control engineer on duty then sends out instructions by teleprinter to the seven main areas, so that distribution over the whole Grid is spread as conveniently as possible. He may continue to revise his instructions for dealing with the expected 8.30–9 a.m. peak up to about 6.30 a.m.

When the demand is liable to exceed the supply, as in recent times with plant shortages, the control engineer's work is very strenuous and responsible. On Thursday, 14th December 1950, for instance, the weather was cold, and snow fell in the North of England. According to incoming data, the estimated peak demand at 8–8.30 a.m. was 13 million kilowatts, and the generating plant in operation could provide not more than 11 million kilowatts. Heavy shedding was necessary. The shortage in Scotland was 20 per cent, and in the South 13 per cent. Power totalling 150,000 kW. was therefore sent north, dangerously overloading the Peterborough–Bourne and Meaford–Crewe lines.

After 8.30 a.m. the demand in the South decreased, and shedding there ceased. But in the North it continued. Though there was now spare power in the South, it could not be sent north, as the lines were already overloaded.

Just before midday the usual drop in the heavy industrial demand

in the North occurred, but shedding was still necessary in Scotland. In the afternoon the demand from the South rose, and power began to flow south in such strength that it endangered the Warrington–Runcorn and Liverpool–Birkenhead lines. If they had cut out, other lines would have been endangered. To prevent this, generation in the North was reduced.

At 12.30 p.m., in order to conserve water for the expected heavy evening peak demand, 180,000 kW. hydroelectric plant in Scotland had to be shut down. Consequently, 110,000 kW. began to flow into the Scottish area previously supplied by the hydroelectric plant, and the loads on the Carlisle–Dumfries and Galashiels–Portobello lines were liable to dangerous increase. It was necessary to continue load-shedding by voltage-decrease.

At 1 p.m. Scotland and North-East England began to import 150,000 kW. to meet increased industrial demands. Danger to the Middlesbrough–York and Lancaster–Kendal lines arose, and at 1.03 load had to be shed in North-East England, though surplus power was available elsewhere.

The bulk of the industrial demand after lunch returned after 2 p.m., and the flow north on the Sheffield–Wakefield and Lincoln–Grimsby lines rose to 155,000 kW. Demand in Scotland and North-East England continued to rise, and shedding was necessary in both areas at 2.55 p.m. Safe loading had been exceeded on the Middlesbrough–York line. While shedding was occurring all over the North, there was a surplus in the South, but the lines could not carry it.

The Scottish hydroelectric plants were brought in at 3.30 p.m., and exported 50,000 kW. By 5.30 p.m., all loads were being carried in the North, Midlands, and North Wales, but complete restoration of supplies was not possible until 6.15 p.m., owing to the heavy domestic and other demands in the South.

Heavy demands were expected on the following day, so the Scottish hydroelectric plants were shut down before 6 p.m. This caused a heavy import into Scotland, which exceeded the safe levels for transmission, so shedding and disconnection of supplies continued until 10 p.m.

The control engineer who recounted this experience said that he handed over to his successor on the next shift not without relief, knowing that he would be at it all again in a few hours' time.

A new National Control Centre has been opened above ground in Paternoster Square. This is more spacious and comfortable, as seen in Plate XV*a*, a picture of the larger National Control Room.

The single engineer, sitting by himself, or with a deputy nearby, controls the whole electricity service of Great Britain, the largest unit of its kind in the world. It is a situation which foreshadows many features of the world of the future.

It is intended to transfer electric power to and from England and France by a submarine cable, as the pattern of daily power demand in the two countries is different, with somewhat differing peak hours; this transfer will allow the reserve generators to be run for longer periods, and reduce the running up costs. An example of the cable being tested is shown on Plate XV*b*.

VI

ELECTRIC LIGHTING AND HEATING

HISTORY loses much of its dramatic force by its inability to tell us who produced fire for the first time and whether he burnt his fingers with it. If a facile pen driven by a vivid imagination could have described the looks of astonishment and awe on the faces of those who witnessed the birth of artificial light and heat, it would have given a picture of an event more important to the future of mankind than all the petty wars and scholastic controversies with which the books are filled. The wonder which it created lingered for many centuries; for long after its value in extracting metals was known, it continued to enter into the most sacred rites of religious observance.

Though the principal use of fire was, and still is, the winning of metals without which few of the tools and appliances of the modern world could be made, the production of light has had a very important effect in enabling man to overcome the disadvantage of circumstance, and it marks one of the most clearly defined steps from savagery to civilization. The admonition of the proverb to rise with the lark and go to bed with the sparrow, though enjoying the warrant of history, would interfere seriously with the customs of the twentieth century, in which the Daylight Saving Bill was, for many years, classified with the annual records of the Sea Serpent.

For many centuries such light as the world required was furnished by the vegetable wick fed with animal or occasionally mineral oil, and it is only a little more than a hundred years since lighting by coal-gas was introduced. During the last fifty years coal-gas has been supplemented by paraffin and petroleum, which had the advantage of portability, and the final method of lighting by flame arose with the calcium carbide and acetylene industry in 1894. The electric light was known in the laboratory from the early years of the nineteenth century, but until cheaper methods of producing electricity than by the use of primary batteries had been invented no commercial application was possible. But since 1879 when the first installation of Jablochoff candles was exhibited progress has been rapid.

ARC LAMPS

The arc lamp developed out of the discovery of the voltaic arc. It was first discovered in Russia, but independently, some years later, by Humphry Davy. He was passing the current from a battery of many cells giving an electro-motive force of 2,000 volts, through two copper rods, and he found that when they were separated by a small amount the electricity sprang across in a sort of flame. The heat caused the flame to rise and form a curve, and from this the name 'arc' is derived. The metal rods were soon replaced by those of carbon, the ends of which glow brilliantly and give far more light at lower cost than could be obtained from any common metal.

The development of the arc lamp gave the first stimulus to the industrial production of electricity. But the flickering, and the burning away of the rods, are serious disadvantages. Arc lamps have been very generally replaced by the more powerful filament lamps which are now available.

INCANDESCENT ELECTRIC LAMPS

The first practical incandescent lamp was the successor of numerous attempts to produce light by passing a current through a fine metal wire. Notable contributors to the solution were A. N. Lodygin, T. A. Edison, and J. W. Swan.

Edison used as a filament a fibre of bamboo which was carbonized by heating in a closed vessel with charcoal. This was cemented to the ends of two pieces of platinum wire which were fused in one end of the glass globe, and served to convey the current to and from the filament. After these wires are sealed in, the globe is exhausted by connecting the other end to an air-pump. When the required degree of vacuum has been obtained the bulb is sealed up. The use of platinum for leading-in wires is based upon the fact that it has the same rate of expansion as glass, and the joint will not, therefore, crack on cooling.

The year 1905 saw a revival of metal filament lamps, for which platinum had been found unsuitable, owing to its low melting-point twenty years before. The first was the Osmium lamp, but the wire is so brittle at ordinary temperatures that it was soon replaced by an alloy of osmium and tungsten, called osram. This wire, again, is not flexible, and is made in short horseshoe-shaped threads, which are joined end to end in series. About the same time Siemens and Halske brought out the Tantalum lamp, and this was from the first a genuine success.

A disadvantage of the Tantalum lamp is the great length of wire which is necessary in order to offer sufficient resistance to the current,

and numerous efforts were made by lamp manufacturers to discover another material. The method of obtaining wire is to draw a thin rod through a series of conical holes of gradually decreasing size in a hard plate, or through similar holes in diamonds. The high melting-point of tungsten was in its favour, but the difficulty was to obtain a drawn wire sufficiently thin and flexible to permit of a considerable length being coiled inside a small globe. But, as Moissan had stated, as a result of his researches with the electric furnace in 1892 (see Chapter IX), that malleable tungsten could be obtained, persistent efforts were made in that direction, and have been crowned with success.

In 1906, the General Electric Company of America took out a patent under which tungsten powder, tungsten oxide, and glucose were compressed and squirted through a hole into the form of rods 5 mm. in diameter and 20 mm. long. These were heated to 1,000° C. in a vacuum to decompose the glucose and oxide, and then to a point just below the temperature of fusion of the metal. The rods were then rolled and drawn white hot, the heat for the latter process being supplied by an electric current passing diametrically through the wire at the die. Today the filament is made of a tungsten wire drawn through a diamond die, and it is suspended on molybdenum supports.

More than one thousand million filament lamps are now made annually, and the process of manufacture has been enormously improved. They are shaped by machinery from glass tubing. This tubing is drawn continuously night and day. Tons of thousands of miles of tubing are consumed for this purpose every year. The exhaustion has to be very thorough to remove oxygen and water vapour. It is accomplished by a pump of the Gaede type (see p. 360), and the objectionable gases are removed by coating the filament with phosphorus. When the filament is heated this volatilizes, and the excess condenses on the glass, where it forms an imperceptible film.

The optimum temperature for producing visible light by heat is 6,500° C. Consequently, the efficiency of metal filament lamps is increased by raising the filament temperature. At very high temperatures, however, the metal evaporates and blackens the bulb, which cancels the gain of efficiency from the high temperature. The evaporation can be checked by keeping in the bulb a quantity of an inert gas such as argon. When this was tried it was found that the gain through suppression of evaporation, due to the pressure of the gas molecules on the filament, was now lost through the carrying away of heat from the filament by the gas molecules, in a process of convection.

In 1913 Langmuir overcame this drawback by coiling the filament in a small volume. This reduced the convection. Then the coil itself was coiled, producing the 'coiled-coil' lamp, with a still further reduction of convection, and gain of efficiency. When this lamp was introduced

in 1934, it brought an increase of efficiency in the domestic lamp of nearly 20 per cent.

Before 1920 most bulbs were made by glass-blowers. Improvements

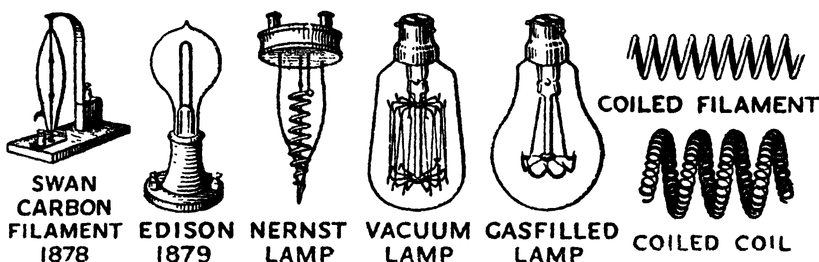


Figure 36. Diagrams of the early and modern methods of wiring the filament of an electric lamp

in glass manufacture and handling have since enabled bulb-making to be done by machinery. The glass fed into the machine must be of very uniform quality (Plate XVII*a*).

It is necessary, too, to control the manufacturing of the filament very closely. This is thinner than a human hair, and yet its thickness must not vary by more than 2½ per cent. A filament of a 100-watt lamp 0·0016 in. thick, which varies unevenly in thickness by no more than one-tenth of the thickness of a human hair, will reduce the life of the lamp by several hundred hours. The thicker part of the filament is cooler than the thinner part. Consequently, molecules tend to shoot off the extra-hot part, and settle on the cooler part. The thick part gets thicker, and the thin part thinner, until the thin part finally burns out.

Many bulbs are frosted, in order to reduce the glare. This is now done on the inside, so that the outside of the bulb remains smooth, and the tendency of a rough surface to collect dust is avoided.

A recent improvement is the introduction of fuses in gas-filled lamps of 40 watts and over. When the filament in such a lamp burns out, it may produce an arc in the residual gas. This causes a sudden drop in resistance, and hence a heavy current in the circuit. The lamp may explode. To remove this danger, a small fuse is mounted in the stem inside the bulb. It is contained in a small glass tube, and connected by a copper lead soldered to the cap. If the resistance in the lamp falls too low, the fuse melts, and cuts the lamp out.

In 1930 the price of a domestic lamp had fallen to 70 per cent of the 1914 price. After the Second World War, the price of an electric filament lamp was 20 per cent lower than in 1939 (excluding purchase tax). These falls in price, in spite of a general rise in cost of living, were due to the improvement and rationalization of production.

It seems, however, that the filament lamp will presently, if not very quickly, be superseded by the electric discharge lamp. Already, discharge types of lamp give very much higher efficiency in amount of light produced for the quantity of electricity consumed (lumens per watt. A lumen is the amount of light falling on one square foot of the inner surface of a sphere of one ft. radius at the centre of which is a light of one candle power).

The development of the electric lamp has stimulated research not only into methods of manufacture, but also on the problems of illumination and seeing, and the effect of different lighting arrangements on the eyes. During the last fifty years new knowledge on these problems, hitherto not investigated, have led to great changes in the design of lighting fittings, so that work and objects should be illuminated sufficiently, and in the best way. The needs of schoolchildren in classrooms, of workers at the bench, of motor-drivers have been investigated.

It is just as important to provide adequate lighting for reading or

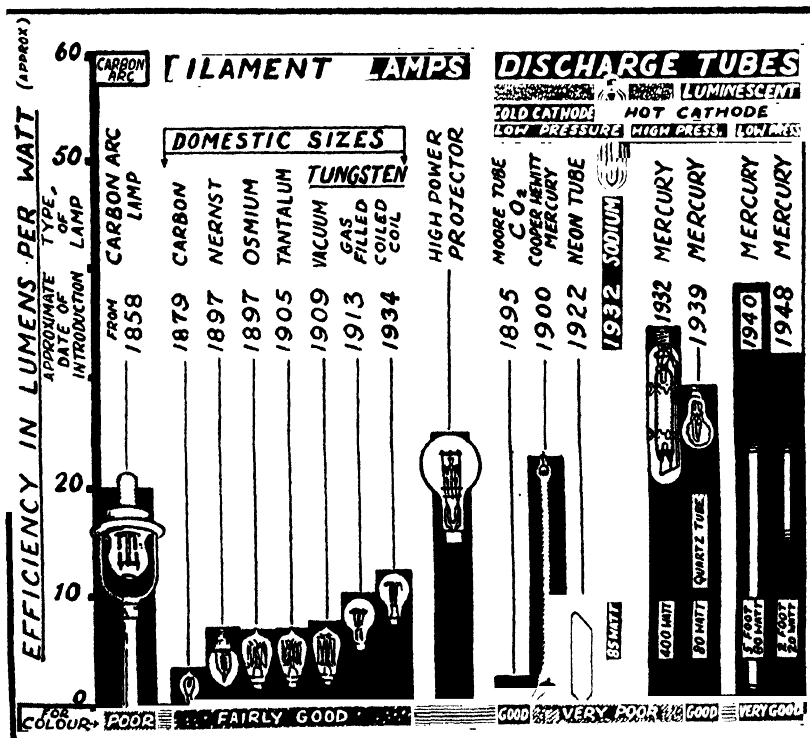


Figure 37. Diagram of comparative lamp efficiencies

needlework in the home, as it is for fine work in the workshop. It has been shown that if the lighting at the work-place on a factory bench for fine work is less than 20 foot-candles, the efficiency of the worker will be reduced, and money will be lost. Below a certain level of illumination, the worker may strain and permanently damage his eyes. Full psychological and physiological efficiency will require a much higher level, which, however, is not easy to demonstrate, though very real.

Much greater quantities of light are required for completely satisfactory illumination. To produce this, much more efficient lamps even than the electric filament are needed. In recent years, the electric discharge lamp has begun to meet this need on a large scale. It is three or four times as efficient as the electric filament lamp, as is shown in Fig. 37.

THE ELECTRIC DISCHARGE TUBE

The production of a glow in the air of a tube by an electric discharge was demonstrated by Hawksbee in 1710, and the proposal that discharge lamps should be used in mines was made in Germany as early as 1744.

The evolution of the modern electric discharge lamp has been slow and arduous. The light produced in a discharge tube is due to the stream of electrons from the cathode colliding with the molecules of the residual gas, and exciting them so that they emit visible light. A voltage of 200 is required to make the cathode emit sufficient electrons. An extra voltage is needed to speed them up, so that the collisions are violent and cause more excitation, which produces more light. In order to be efficient, the part of the voltage which produces the light should be large in proportion to the 200 required for the release of the electrons. Hence the tubes are long, and the voltage up to 10,000. The lamp remains relatively cool at about 70° C., and its colour depends on the kind of gas in the tube. Neon gives the familiar red light. Helium gives a brownish-white light. Carbon dioxide gives a light very similar to daylight, but low in intensity. Mercury gives an intense bluish light.

The application of a high voltage to a cold metal cathode is not a very good way of producing the stream of electrons required. Hot cathodes consisting, for instance, of thoriated tungsten heated until it glows are much more effective, and require not more than 20 volts.

One of the first of the hot-cathode lamps was the sodium vapour lamp. This gives an intense yellow light, which is monochromatic, or pure. The practical problems of manufacture were great, as sodium vapour attacks ordinary glass. After much research, a method of coating the inside of the tube with a specially resistant glass was discovered.

As the sodium lamp is very efficient, giving 57 lumens per watt (compared with 10 lumens per watt in the ordinary filament lamp), it can be used where the peculiar yellow and monochromatic light is no disadvantage, as in street lighting. It is useful, too, for illuminating coal-sorting machinery, as the difference between good coal and stone slate is enhanced by the pure yellow light, so that it is more easy to pick out the waste.

In order to keep the sodium vaporized, the tube is surrounded with a double wall containing a vacuum, like a vacuum-flask.

Mercury vapour lamps give about 34 lumens per watt. The intensity of light from them is increased by pressure. Special hard glasses have been made so that such lamps can be run at pressures of one atmosphere. By using water-cooled quartz tubes, the working pressure may be raised to 100 atmospheres. Such lamps may give 80 lumens per watt. Besides giving more light, the higher pressure, which increases the turbulence of collisions in the tube, also gives a more mixed and agreeable light. The colour can be improved by putting small quantities of other metals, such as cadmium, in the tube.

Powerful discharge lamps, in which the arc may only be about an inch long, between blocks of tungsten, are made for cinema projectors. Such lamps with 'compact sources' are about five to ten times as efficient as tungsten filament lamps.

The increase of efficiency by raising of pressures and temperatures leads to mechanical problems. There are other ways of increasing efficiency which depend on entirely different principles.

The low-pressure mercury lamp emits a great deal of ultra-violet rays, which are invisible, and indeed bad for the eyes. It has been found possible to convert the ultra-violet rays into visible light through the phenomenon of photo-luminescence, and thus utilize for illumination energy which would otherwise have been wasted.

Various substances have the property of emitting visible light when ultra-violet rays fall on them. Hence, when the inside of the tube of a low-pressure mercury lamp is coated with one of these substances, much of the ultra-violet rays produced in the tube falls on the coating and is converted into visible light, which augments the visible light from the mercury arc. This extra light is cold, and the tube remains cool, as photo-luminescence is not dependent on temperature.

The coating, besides increasing the amount of visible light, makes the lamp safer for the eyes, by removing the ultra-violet rays.

The luminescent tube is made in sizes as small as 15 watts. The colour and quality of its light can be largely controlled by the composition of the coating. With its efficiency, agreeableness, and safety, it will probably become the chief lamp of the future.

The first experiments on coating discharge tubes with luminescent

materials were made by Becquerel in 1857. (The family interest in luminescence led a later Becquerel to discover radioactivity in 1896.) The modern results have been obtained only by most extensive and determined research by many scientists, and teams of research workers. It had been noticed in 1886 that the presence of impurities was necessary for the activity of luminescent substances. In 1904, Lenard and Klatt published an account of an investigation of the role of impurities in 800 varieties of luminescent sulphides.

The use of rhodamine to improve the colour of light from mercury lamps was proposed in 1903. In 1935 H. G. Jenkins found that zinc orthosilicate and calcium tungstate compounds give a bright yellow light under the radiation from the discharge in neon, which is itself red in the visible region.

Luminescent materials are strongly affected by very small variations in the quantity of activating impurity which they contain. A few parts in a million may be sufficient. Consequently, they must be very carefully prepared. This adds to their expense. Natural materials have been superseded by synthetic products, whose composition can be more carefully controlled, and for this reason be ten times as effective. The best kinds of activators, and the optimum proportion of these, are determined by research.

A particularly interesting material is calcium halophosphate. It radiates a variety of colours, according to the quantities of activator used.

Fluorescent lamps giving white light were first used on a large scale at the New York World Fair in 1938. The number used was sufficient to provide experience in the problems of their mass-production.

In Britain, the manufacture of fluorescent lamps was standardized on a single 80-watt five-foot type, giving a colour which approximated to daylight. The efficiency was 35 lumens per watt when new, and 24 lumens per watt during a life of 1,500 hours. These lamps were made in enormous quantities for the lighting of factories and offices for night-work, and during the blackout. By 1952 the efficiency had been raised to 50 lumens per watt when new, and 43 on the average for a life of 5,000 hours.

The life of a tungsten filament lamp is about 1,000 hours. Thus the

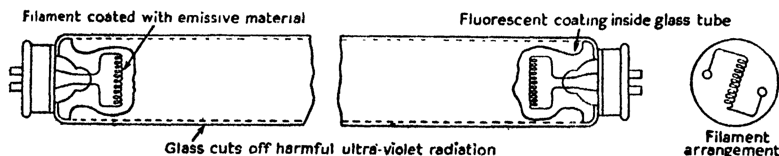
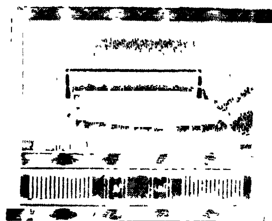
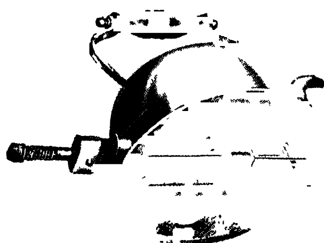
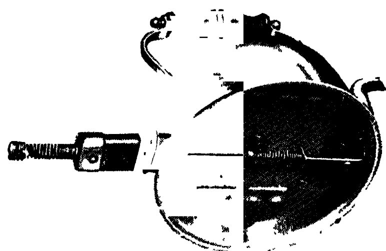


Figure 38. Low-pressure hot-cathode fluorescent tube

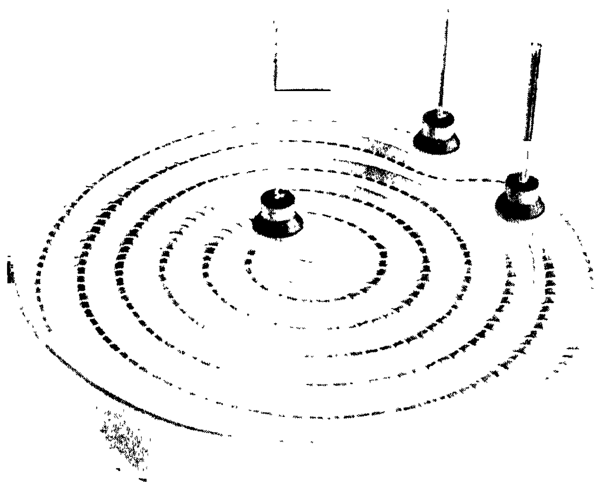


XIX*a*. Parabolic electric fire

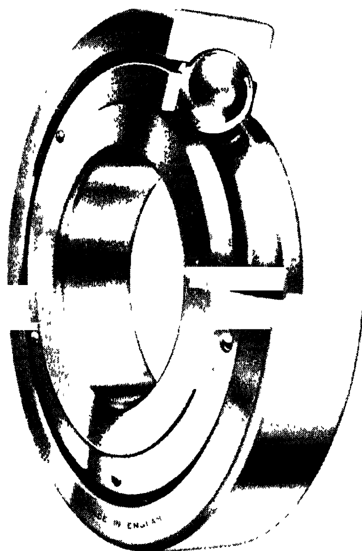


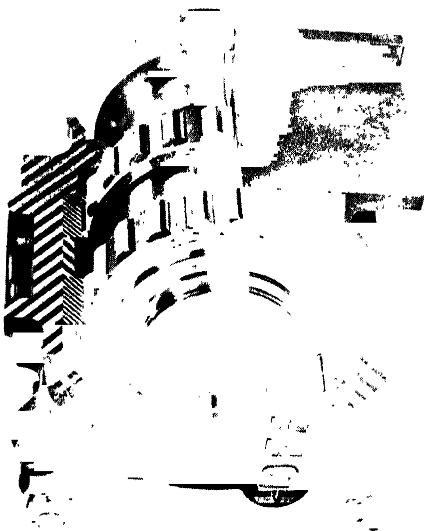


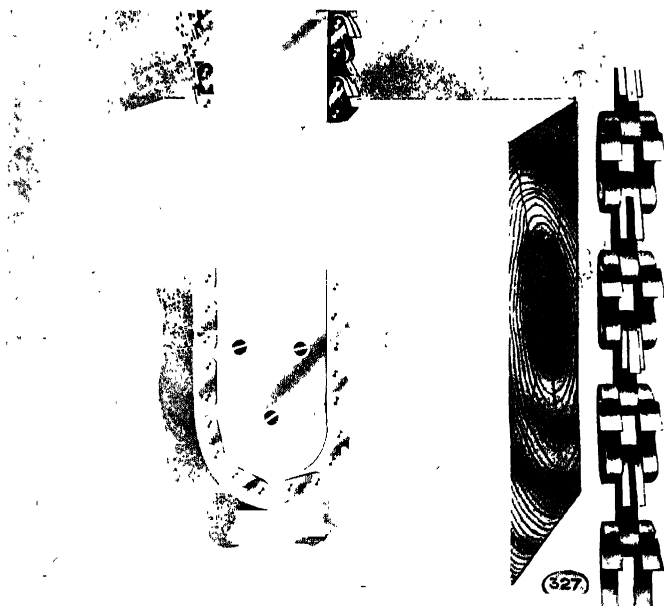
XIX*b*. Automatic safety kettle.
Closed position and open position



XIX*c*. An electric boiling plate; construction with resistance spiral enclosed in position


(*Hoffmann Mfg. Co. Ltd.*)
xx*a*. A ball bearing


(*Hoffmann Mfg. Co. Ltd.*)
xx*b*. Axle box with roller bearings



xx*c*. Mortising machine with chain cutter

fluorescent lamp, with a life of 5,000 hours, lasts five times as long, besides giving about five times as much light for the same consumption of electricity. This great increase in efficiency more than makes up for higher initial cost.

The tubes for fluorescent lamps are made in tens of thousands. The fluorescent powder is made into a thin cream, with a nitro-cellulose binder and a solvent, and blown inside the tube (Plate XVIII*a*).

This is drained and put in a dryer. The timing of the coating and drying operation has to be precise in order to get good results. When dry, the tube is baked in an oven to remove the nitro-cellulose binder. The thickness and dispersal of the coating is tested by a photo-electric cell. If there is a variation of more than 0·05 gramme per foot the tube

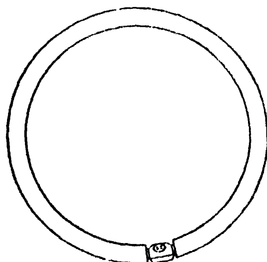


Figure 39. A 40-watt Osram circular fluorescent lamp; the diameter of the circle is 16 in. and of the tube 1¼ in. The colour is mellow

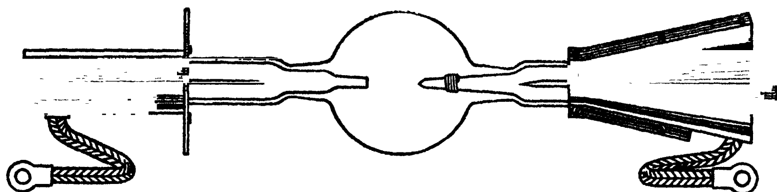


Figure 40. A 2½-kW. Compact Source high-pressure mercury vapour lamp. It is made of quartz and its colour is corrected by the addition of cadmium vapour. It is used for film studio lighting

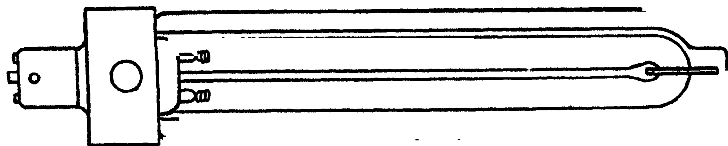


Figure 41. A 60-watt sodium lamp. The inner tube containing the sodium discharge is surrounded by a detachable vacuum-flask jacket. The colour is pure yellow

is rejected. The fluorescent light from the coating comes from its inside. If the coating is too thick it cannot get out, if it is too thin there is a danger of discoloration owing to the constituents of the glass combining with mercury inside the lamp.

The tube is then exhausted, and the gas extracted from the coating and the cathodes. A small quantity of mercury is let into the tube, and enough argon to raise the pressure to $\frac{1}{200}$th of an atmosphere (Plate XVIII*b*).

After the tubes have been tested for leaks by a high-frequency oscillator, they are aged on a revolving rack, being lit as they would be under normal conditions.

ELECTRIC HEATING

When a current of electricity passes through a conductor heat is produced, and the greater the resistance offered to the passage of the current the greater is the proportion of the electricity which is converted into heat. The arc and filament lamps, which have already been described, are illustrations of this fact, though in those cases the heat is desired only in order to raise bodies to the temperature at which they produce the greatest amount of light, and the heat formed at the same time is so much waste.

But while the problem of obtaining a greater amount of light from a given amount of electrical energy has so far proved a matter of difficulty, there is no trouble in converting a large quantity of electricity into heat. Moreover, there is an absence of smell, smoke, and ash inseparable from coal and almost inseparable from oil, together with a possibility of regulation and adjustment that gives heating by electricity certain advantages, especially for auxiliary heating.

Attention will be drawn to the use of the electric arc in welding, in Chapter VII, and the whole of Chapter IX is devoted to a great range of manufacturing processes in which the electric furnace is now employed. Consideration will therefore be confined in this section to some of the domestic applications.

The material in which the heat is produced may either be a thin wire or strip of metal having a high resistance, or a fabric composed of metal and asbestos, or a thin metallic film deposited upon a strip of mica, or rods of carbon which have been coated with a preparation that prevents oxidation. Of the many types available for heating rooms we have selected one manufactured and recently put on the market (Plate XIX*a*).

Some of the most ingenious electrical heating devices are intended for use in the kitchen. Plate XIX*b* shows the Metro-Vick automatic safety-kettle. If an electric kettle boils dry the heater becomes too hot

and may burn itself out. This involves the expense of a new heating element. But in the kettle illustrated the electricity is disconnected by ejection of the heater. This action depends upon the fact that the bottom of the kettle is domed, and the heater is placed just below it. When the water boils away beyond a certain level, the temperature of the dry centre of the dome rises, expands upwards, and releases a spring plunger, which forces the connector from its socket. By means of an additional attachment, consisting of a mercury switch which cuts off part of the current when tilted, this kettle can be so arranged that it will not boil over.

The production of heating appliances for use in the kitchen has called for a considerable amount of experiment. The conductor in which the heat is produced should be protected from liquids or solids that may fall upon the stove or hot-plate. It must be adequately insulated so that there is no possibility of the cook receiving a shock. The heat must pass readily from the hot wire, ribbon, or rod to the vessel or food which is to be heated or cooked. How these conditions are secured is well illustrated by the construction of the Cosmos type of boiling-plate (Plate XIX*c*). This consists of a cast-iron disc with a spiral groove on the under surface. A flexible magnesium 'tube', through which passes a nickel-chromium wire spiral, is laid in the groove. When this is treated with steam in a closed vessel at a temperature not exceeding 300° C. the magnesium is converted into crystalline magnesium hydroxide, which swells out and fills the groove. The magnesium hydroxide is a sufficiently good electrical insulator to prevent an electric current in the spiral escaping to the iron plate, and yet a sufficiently good conductor of heat to allow the heat to flow through from the spiral. The space inside the heating coil is filled with alundum cement, the groove is covered with an asbestos plate, and that again by a cast-iron plate which forms the under-surface of the heater.

A plate of this kind, starting all cold, will raise 2 pints of water to the boiling-point in 8½ minutes, or 5 pints through the same range of temperature in 14¾ minutes. When the plate has once become hot 4 pints of water can be boiled in less than 8 minutes.

Heating devices are modified according to the position they are to occupy and the purpose they are to serve. One great advantage claimed for electric cookers is that there are no products of combustion in the oven, very little air circulates through it, and the loss of weight of the food is very small. By other methods of cooking this loss lies between 25 and 33⅓ per cent, whereas in the electric oven the loss is never more than 10 per cent. An ordinary lunch or dinner for four to six persons can be cooked for an average cost of 3½*d.* when the cost of electrical energy is a penny per unit.

An oven used by bakers and confectioners is shown in Plate XVII*b*.

The loaves or confectionery are placed on trays which hang from chains passing over toothed wheels. The wheels turn at such a rate that a tray passes the oven door, on the right of the illustration, once each minute. This oven has six trays. With eight trays each 73 inches long by 17 inches wide the baking space is 70 square feet. There are no hot spots where the cakes are blackened or cold spots from which they emerge pale and anæmic. Every cake passes through hot and cold spots in turn, so that each one is cooked to the same attractive tint.

Among the numerous domestic heating appliances to be seen today in the shop windows are electrically heated irons for the laundry. This, again, is a case where careful regulation of the temperature is desirable to avoid scorching. Thousands of people today use an electric toaster on the breakfast-table, and find that the pleasure of really hot fresh toast is well worth the sixteenth of a penny per slice which the process costs them. If this method were general—and it might easily become so—the miniature trident fork will one day occupy an honoured place in a museum of antiquities.

We cannot close this chapter without emphasizing again the fact that one of the final achievements of applied science is cheapness. Scientific discovery and invention enlarges the comforts and conveniences of more and more people. At first, some commodity may be scarce and expensive. Then the engineer, the chemist, the scientific manufacturer bring their minds to bear upon its production, and from a luxury to be enjoyed only by the rich it becomes almost a necessity for all. In this way fine linen and silk, lace, many kinds of food, the electric light, comfort and speed of travel, and a host of other results of invention are enjoyed by people who, in the absence of discoverers and inventors, would have regarded them with hopeless longing. And if this progress has not sufficiently lightened burdens, nor lessened misery and want, it is not so much the fault of scientific man, but the failure of people to realize the trend and meaning of the age in which they live, and to see that its possibilities for human welfare are fully achieved.

VII

SPEED AND ECONOMY IN PRODUCTION

It is a trite saying that we live in a mechanical age. Every operation ordinarily performed by man that can be carried out by a machine is, or should be, handed over to the care of whirling wheels, rocking levers, and rolling teeth. The numerous electric laundries, machine bakeries, and automatic machines add their evidence to the bicycle and the motor-car. And the applications of machinery in manufacture and daily life are becoming so numerous that the smaller steps in progress escape observation.

While it would be impossible in a book of this size to notice a tithe of the contrivances by which time and labour are saved, and greater accuracy secured, in modern workshops, it would be equally undesirable to ignore altogether the general progress which has been made during the last fifty years. But it will be clear that the examples must be chosen because of the generality of their application, the striking character of the scientific principles involved or the results achieved, or the extent to which they represent the magnitude and power of human effort.

Let us therefore consider first some ways in which time and energy are economized in the workshop.

THE TRANSMISSION OF POWER

Most workshops were formerly equipped with long lines of overhead shafting from which the machines below were driven by belts and pulleys. In this system, the shafting had to rotate continuously whether one or fifty machines were working: the power required to drive it and the wear and tear were practically the same for one machine as for all. The belts required attention, and if one broke the machine was idle. If the main belt gave way the whole of the work came to a standstill. This applied not only to engineering workshops, but also to all factories where machinery was employed. For instance, in the textile factories it was the custom to effect the main drive from the engine by ropes

working in grooved pulleys, and to drive the machinery from the main shafting by leather belting. A glance into many shops revealed an overhead mass of whirling wheels and a veritable forest of belts.

The practice has rapidly gained ground of using electrical power and driving each machine by an independent electro-motor. When the machine is not working no current is used, and at any time only so much is consumed as is necessary for the work in hand. The cumbrous method of altering the speed of a machine by a belt and stepped or cone pulleys is then unnecessary, the mere adjustment of a lever being sufficient to alter the speed. The textile factories of Lancashire, which had hitherto held aloof, began to adopt the method and thousands of small electric motors of from ½ to 1 h.p. were installed.

The old type of bearing for an engine or heavy machine consisted of two parts—a cast-iron frame and a brass or gun-metal bush, which was cut in half so that it could be adjusted for wear. In many cases the bush had wide grooves cut along its inner surface in the direction of the axis, and filled with a white metal. This white metal was poured in in molten condition when the shaft was in place, and the brasses adjusted so as to clasp it loosely.

A little consideration will show that it is extremely difficult to get a perfect fit between a heavy bearing and shaft, and any departure from true alignment will lead to excessive friction and wear at certain points. The white metal is one of many alloys on the market, called anti-friction metals. A typical anti-friction metal, etched and examined with the help of a microscope, will be found to consist of hard crystals embedded in a softer matrix. These hard portions resist wear, while their soft bedding enables the metal to adjust itself to pressure. By casting it in grooves after the shaft is in position it soon adjusts itself to the surface so that the pressure and wear are evenly distributed. Moreover, it is at all times easily replaced at far less cost than would be required to replace worn brasses.

Such bearings do not overcome the difficulty that however well they may be lubricated the rubbing absorbs a considerable amount of energy. As the rolling of two surfaces over one another is very much easier than sliding, bearings are made which consist of a ring of case-hardened steel rollers mounted in a circular frame surrounding the shaft. These offer an extraordinarily small resistance to pure rotation, but if there is any end movement this involves sliding and its attendant disadvantages. The most flexible bearing, however, is one consisting of one or more rings of steel balls running in a groove or race in the body of the bearing. Ball bearings have long been used for bicycles, and they found early application in such machines as required high speeds for small loads, or slow speeds and heavy loads. Later, they were applied to all kinds of light and heavy machinery at all speeds.

The Hoffmann Manufacturing Co., Ltd., of Chelmsford, which was formed over fifty years ago, and is one of the pioneers of modern bearing manufacture, now produces a wide range of complete ball and roller bearings, and in addition supplies nearly one million loose balls per day to industry. To give some idea of the scope and degree of accuracy of the work involved it can be said that the balls, which are made of hardened high carbon chrome steel, range from $\frac{1}{64}$ in. to 4 in. in diameter and all the balls of one size are guaranteed to be within 0·0001 in. of one another both in sphericity and size.

The precision and reliability of present-day ball and roller bearings contribute in no small measure to the efficiency of many modern high-speed machines, and the fitting of ball and roller bearings is standard practice in applications ranging from jet engines to gyroscopic instruments or steel-works cars to roller-skates.

Illustrations of the most popular types of ball and roller bearings are shown in Plates XX*a* and XX*b* respectively, from which it will be noted that a complete bearing consists of an inner and an outer race in which running tracks are formed for the balls and rollers. These races which may be of high carbon chrome steel or carburizing steel are fully hardened during manufacture and accurately ground to size. In most cases the balls or rollers in a bearing are separated from one another by means of a member known as a cage, and this may be made in a variety of materials including brass, bronze and mild steel.

The use of ball and roller bearings in the axle-boxes of locomotives and rolling stock is becoming more widespread in the United Kingdom, and Plate XXXIV*b* shows the first gas-turbine electrical locomotive built in Britain. This was designed and constructed by Metropolitan Vickers Electrical Co., Ltd. (see p. 257), and is fitted with Hoffmann roller bearing axle-boxes throughout. These were adapted especially to avoid axle transverse play relating to the bogie, in order to secure good riding at high speed. The boxes are very closely guided with initial clearances of only 0·10 in. in both horizontal directions. The wearing surfaces on the boxes are made of manganese steel, and the guides of oil-hardened steel, grease being used as the lubricant.

Ball and roller bearings are widely used in a number of less spectacular applications and for many years the London Underground Railways system has been running on roller bearing axle-boxes similar to that shown in Plate XX*b*.

They are used in artificial limb joints, dentists' drills, the Post Office Railway (roller bearing axle-boxes), Sutton Coldfield television mast, the 'Thunderbolt' and 'Bluebird' (the land speed record-breaking cars of Capt. G. E. T. Eyston and the late Sir Malcolm Campbell), bicycle motors, television cameras, angling spinners, and very many other applications requiring the maximum reduction of friction.

In transmitting motion to a machine, or from one part of a machine to another, toothed wheels are frequently employed. The wheels may be made of cast iron or steel, and the teeth cast or cut in the same material, or made of wood, raw hide, or other material which reduces noise and shock. The aim in designing wheel teeth is to secure rolling between the teeth in contact, and there are several beautiful devices for shaping the surfaces. As a mechanism, toothed wheels are older far than the steam-engine, so we shall say nothing further about them here beyond the remark that they have recently come into use for ship propulsion. Attention is drawn elsewhere in the book to the fact that C. A. Parsons succeeded in cutting gearing that transmits 98 per cent of the power supplied to it, and was very nearly noiseless in action. The method by which a relative absence of noise has been secured is interesting.

The method of cutting the teeth was to fix the blank wheel to a table which was rotated by a worm. As the table rotates, a cutter carves out the spaces between the teeth. Any small error in the machine was found to recur at regular intervals, so that it accumulated at certain parts of the wheel being formed. Parsons overcame this difficulty by fixing the blank wheel upon a second table which had a 'creep' of about 1 per cent over the first. The main table was then rotated about 1 per cent slower and the inaccuracies inherent in the gearing of the machine were distributed evenly over the new wheel.

It will be clear that in the case of belt driving, if there is to be much difference between the speeds of two shafts, a considerable distance between them is absolutely necessary, or such a small portion of the rim of the smaller pulley will be gripped by the belt that much slipping will occur. On the other hand, toothed wheels become unnecessarily large when the shafts are far apart, and they are liable to be noisy. The method first used extensively on bicycles, in which a chain passes over two toothed wheels or sprockets, is much more elastic in regard to distance, is free from any possibility of slip, and can be made to work at least as silently as any other device for transmitting power.

Chains are used in enormous quantities for cycles and motor-cycles, and many kinds of machine, both small and large. They are used for transmitting power, and in recent years they have been adopted widely for conveyors, which have such an important part in the organization of mass-production. Fifty years ago chains to transmit 50 h.p. were rare; today, chains for transmitting 4,000 h.p. are made. While individual electrical drive has largely been introduced for driving machines, in the textile industry considerable use is still made of chains. They increase the efficiency of transmission of power up to 98½ per cent.

One of the pioneers of chain development has been the Renold and Coventry Chain Company Ltd. Hans Renold, the founder of one side of

the firm, developed the silent chain. This consisted of inverted steel links with teeth on one side, which engaged the teeth of the sprocket wheel. The surfaces of the teeth on the links were flat, and at the time when they were introduced, could be made much more accurately flat than the rollers for roller chains could be made round. Consequently, because of their better fit, they could be run faster and were more silent than roller chains.

The improvement of precision engineering has since enabled the precision of manufacture of roller chains to be greatly improved. Roller chains are much lighter and offer less resistance to the wind when running at high speed. The development of the chain owed much to Hans Renold's ability for devising automatic machines for making the parts.

The chains used on racing motor-cycles have to stand enormous stresses. For instance, the chain on the racing Norton shown in Plate XXI*a* travels at 7,000 ft. per minute at maximum speed (up to 130 m.p.h.). The engine is then developing about 50 h.p. These chains run unprotected, which from the engineering point of view is a very severe condition, and they have a drip-feed lubrication.

Motor-cycle chains are of ½-in. pitch, i.e. the distance between the axis of one roller and the next. When the chain is made, a 50-in. length will not vary from that size by more than 0·075 in., though in that length of chain there are no less than 500 components. The precision of the individual components is thus very high.

When a chain is used in a motor-cycle race such as the Tourist Trophy in the Isle of Man, it is strained to the limit, and generally does not last beyond the few hours of the race. The exposure, the lack of sufficient lubrication, the irregularity of engine torque and the distortion in the alignment of the machine owing to the shocks it receives, increase the stresses on the chain. At the end of the race it may sag almost like a piece of cloth.

The chain consists basically of a series of inner and outer links held together by bearing pins. Each member of the chain contains a circular bush which is fixed rigidly to the inner chain-plates. A bearing pin goes through the bush, and is fixed rigidly in the outer chain-plates. A roller is freely mounted on each bush between the inner plates. Thus there are two sets of bearing surfaces, between pin and bush, and between bush and roller.

All of the parts are made of steel carefully chosen to suit its particular duty. The correct heat treatment is very important in giving it the appropriate properties and strength.

The capacity of the chain depends on the area of the bearing surfaces between the pin and its bush, and not on the strength of the side-plates and pins. The chains do not 'stretch'. The increase in length that occurs

is due to the wear of the bearing surfaces. Wear is rapidly increased when the bearing surface pressure becomes excessive through overloading the chain. Wear is rapid, too, when lubrication is grossly neglected, even if the chain is of the correct size for the duty to be performed.

The correct design of the shape of the teeth on the sprocket is of great importance. It aims at providing the maximum area of contact between the roller and the tooth, not only when the chain is new, but also when worn. The design ensures that the load is spread on the various rollers as they pull the wheel round, and is not concentrated on the single tooth where the chain is leaving the wheel.

In Fig. 42, the distribution of load is shown on a suitably designed tooth.

It will be observed, also, that when the chain is bent in going round

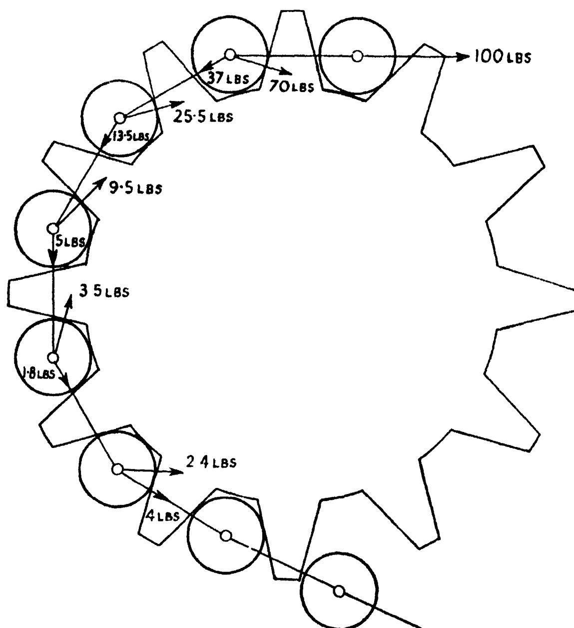


Figure 42. The distribution of load on a roller chain with a suitably designed tooth

the wheel, the axes of the pins form a polygon. Unlike a belt, a chain does not bend into a portion of a circle. If the wheel is rotating at constant speed, the chain speed will vary cyclically, owing to its varying distance from the centre of the wheel. At high speeds, this is liable to

set up vibrations, and to increase torsional stresses. These can be kept down by using as many teeth as possible, so that the polygon of pin-axes approximates more and more closely to a circle.

Very large chains are used for driving electric generators in the big new French tanker *Berenice*, which has a displacement of 30,000 tons.

Two alternating current generators of 500 kW. are driven by chains off the main propeller shaft. Their pitch is 2 in., and each is rated to transmit 800 h.p. (Plate XXI*b*).

Plate XX*c* shows a mortising machine which carries cutters on every link, and is made to rotate round a frame, while it is pushed endwise into the wood. The front portion of the block is removed to show the shape of the mortise. Compared with the tedious process involving the brace and bit, hammer and chisel, the machine performs the operation with remarkable speed and accuracy.

The ingenious coal-cutting machine invented by Austen Hopkinson applies chains carrying cutters to undercut coal. Here the problem is to undercut the seam of coal so that it can be more easily removed by blasting or the pick. It consists of a block chain passing round two large sprocket wheels. The blocks are specially designed to carry tool holders, and can easily be detached from the chain for renewal. As the wheels revolve, the cutters rip out the coal in the same way as the teeth of a saw.

An extremely interesting and effective means of transmitting power with a variable speed which is entirely under control is illustrated in Plate XXII. It consists of two hydraulic units, one acting as a pump and the other as a motor. They may be in the same casing or some distance apart and connected only by the pipe which conveys the fluid —generally oil—from one to the other, while obviously the two shafts may be at any angle. Both pump and motor consist of a number of barrels mounted round the shafts. Each barrel has a bucket piston and a rod which presses at one end upon the bottom of the bucket and at the other upon an inclined disc. The speed of the driven shaft depends upon the rate at which oil is supplied to its motor. The driving shaft rotates at constant speed but the rate at which oil is pumped is varied by altering inclination of the disc, and thus varying the stroke of the pistons. The speed of the driven shaft may, therefore, vary from that of the driving shaft in one direction down through zero to a similar speed in the reverse direction.

From Plate XXII it will be observed that the pump and motor are set back to back and that the centre valve-plate between them admits oil from one to the other. Only a small quantity of oil is required and that is used over and over again. On the extreme left will be seen the arrangement for altering the inclination of the disc and thus varying the speed. This and similar contrivances were largely used during the war for the

elevation and training of big guns. In times of peace it finds its greatest use in the steering gear of ships; for capstans, hoists, winches and cranes; for printing machinery and hydraulic presses. It has been made to operate a swing bridge, to drive machine tools, and for many other purposes.

While the foregoing devices for transmitting energy are improvements on old and well-established methods, the one next to be described is based on an entirely new principle. Everyone knows that sound is propagated through a medium, solid, liquid, or gas, as a wave-motion. Particles in the immediate neighbourhood of a sounding body are set in motion, and the motion travels outwards in ever-widening circles like the waves formed when a stone is thrown into a pond. Each particle in a wave swings backwards and forwards about its original position, causing alternate compressions and rarefactions. It is the motion and not the particles, which reaches the drum of the ear and causes the sensations which we recognize as speech, music, laughter, or noise.

The speed of sound in any medium depends upon the density of that medium. In air at the ordinary temperature it is about 1,200 ft. a second; in water it is nearly 5,000 ft. a second, and in elastic solids it is much more rapid. In the denser medium the motion travels farther than in one less dense. Thus a faint scratch on the end of a rod of wood or metal can be heard quite easily by a person who places his ear at the other end. The distances at which sound can be heard under water led to the development of submarine signalling described in Chapter XVI, and was proved of immense importance in the detection of submarines during the war.

About thirty years ago, the Roumanian engineer Constantinesco discovered that if water was contained in a pipe, and a series of impulses, corresponding in frequency to waves of sound, was applied by means of a piston at one end, the motion could be communicated to a piston at the other. The arrangement is shown diagrammatically in Fig. 43, and though there are a number of details which have to be taken

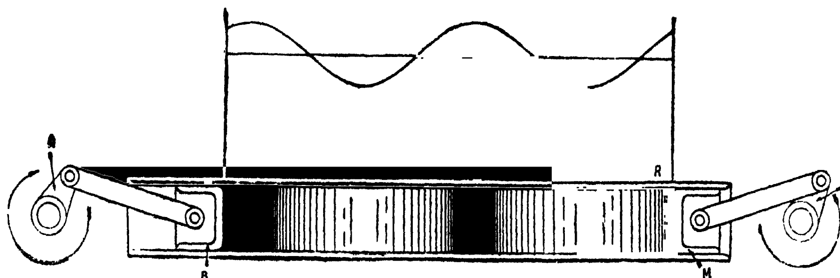


Figure 43. Diagram to explain wave transmission

into consideration, the principle upon which the apparatus works will be clear. It was used during the First World War for timing the fire of machine-guns mounted on aeroplanes, and firing between the blades of a propeller; and 30,000 of these appliances were made by W. H. Dorman & Co., of Stafford, for the British and Allied Forces before the Armistice. It is now being applied by the same firm to rock-drills, riveters, and other tools.

There are two pistons which are driven from the shaft in the centre. The two spheres are known as capacity vessels and their purpose is to absorb surplus energy which, under certain circumstances, may be produced. The speed is such that 40 impulses per second or 2,400 per minute are given to the water, and these are transmitted to the tool through a 'Flexstel' pipe, the construction of which will be clear from Plate XXIII*a*. The drill may be mounted on a cradle or other form of stand. Water passes to the drill point by a tube through the hammer, and the amount can be regulated by a screw cock. No fine dust is produced. The drill is rotated at each stroke by a small independent wave motor operated from the main supply.

Up to the present the most promising development appears to be in rock-drills for mines and quarries, but it is also adapted for any purpose for which compressed air has hitherto been applied. The transmission of energy by compressed air is so wasteful that the new system ought to prove a considerable advantage.

MACHINE TOOLS

Anyone who has been through an engineering workshop will realize that the machines it contains can be classified in groups according as the tool or the work moves. In the drilling and shaping machines holes are bored, or a plane surface is made on a piece of material which is fixed rigidly to the table of the machine. In the lathe, the boring machine, and the planing machine the work as a rule moves and the tool is fixed —perhaps it should be explained that a boring mill is a lathe without a back centre, the object being bolted to a horizontal or vertical face plate. There are two or three interesting scientific principles involved in the use of these machines, a better understanding of which has had an important effect on recent design. So long as the cut is continuous and in the same direction it is a matter of very little consequence whether the work or the tool moves, and there are generally advantages in having a fixed tool. The lathe for the external surfaces of long objects and the horizontal or vertical boring mill for internal machining and facing short objects are not likely to change. In the planing machine, however, the object moves backwards and forwards and—originally— the cut was made only one way. A saving of time was effected by fixing

the cutting tool in a reversible socket in which it was rotated automatically at the end of each stroke, thus cutting in both directions. But if the object is at all heavy a good deal of energy is wasted in starting, stopping, and reversing the direction of the table, and many machines are now made in which the object is fixed and the tool holder travels backwards and forwards. But one tool cutting at once will not satisfy the modern demand for speed, and frequently two tools are set to work at once, one taking a roughing and the other an intermediate or finishing cut. This demand is partly responsible for the development of the modern milling machine. In this the tool is a hard steel wheel with teeth shaped with the correct angle for cutting, while the work moves backwards and forwards beneath it. In one sense this disobeys the rule given above, in which any reciprocating motion should be given to the lighter part. But the milling cutter moves relatively fast and the work slowly and with few reversals. The finish from a milling tool is very much smoother than that from an ordinary tool, because the large number of teeth following one another closely are wide enough to permit of overlapping. A smooth surface instead of a series of channels is formed. As an example of the work done in this way Plate XXIII*b* shows the Acme screw thread, and the cutter by which it is chased at one operation.

Perhaps no change is greater in workshops than the wide application of grinding. The most accurate work is now performed by a carborundum wheel which, spinning round at a high speed, tears off the metal with its thousand points and creates showers of sparks in its passage over the surface. From a tool used in the fettling shop for removing roughly the surplus metal on castings, the grinding machine has within fifty years become an instrument of precision, to which has been entrusted the most accurate workmanship that modern manufacture demands. For making the thin pins that hold together the links of a bicycle chain to the smoothing of an armour plate, the engineer depends upon the grinding machine.

The efficiency of all the machines which depend upon a steel cutter has been enormously increased since 1900. In Chapter VIII the discovery of high-speed tool steel by Messrs. Taylor and White, of the Bethlehem Steel Company, will be described. This steel enables the speed of overhead shafting to be increased from 90 to 250 r.p.m., and raises the amount of metal which can be torn off per hour from 30 to 137 lb. Since then a large number of other special tool steels and cutting materials have been produced, some of which owe their properties to the presence of vanadium, which has a most powerful influence upon the steel with which it is alloyed. The result is that work which formerly took weeks is now executed in days.

CARBIDE CUTTING TOOLS

The early special steel cutting tools, containing high percentages of carbon, silicon and manganese and about 5 per cent of tungsten, had a cutting-speed of about 25 ft. per minute. The introduction of high-speed steel at the Paris Exhibition in 1900 started a revolution in cutting tools, and the introduction of cemented carbides in 1925 began another period of great development.

High-speed steel contains up to 22 per cent of tungsten and 12 per cent of cobalt. It retains its hardness at a red heat.

Stellite, an alloy of cobalt chromium and tungsten, can be used at higher speeds than high-speed steel, and has the advantage that it can be cast and welded. It has a higher tensile strength than carbides.

Tungsten carbide tools were introduced in 1926. Their composition has been varied by the introduction of titanium, molybdenum, chromium, vanadium, tantalum, and cobalt. The material consists of a matrix of cobalt, through which tungsten-carbide is dispersed.

The material is made by grinding the constituents to particles about 0·0001 in. in size, and mixed in appropriate proportions. The powder is then subjected to a very high pressure at about 450° C. It is then sintered in an electric furnace at about 1,500° C. The product is only about 15 per cent less hard than diamond, and cannot be shaped by any process except grinding. It is brittle, and is easily broken, for example, by machine vibration.

Tungsten carbide is more successful for cutting cast iron than steel. It tends to make chips with steel which weld themselves to the end of the tool, and may break it. The carbide cutting piece, after being ground to shape, is welded on to the steel tool. The welding or brazing is easier if the cutting material contains tantalum and titanium.

Carbide cutters will work at much higher cutting speeds, but are more fragile and expensive. Consequently, high-speed steels are still much used, especially for machining forgings.

The comparative performances of ordinary carbon tool steel, high-speed steel, and Carboloy (tungsten carbide) for the same feed and depth of cut were found by O. W. Boston to be:

	Cutting speed in ft. per min.	*Life in minutes*	*Volume of metal removed cubic in. per min.*	*Net horse-power consumed*
Carbon tool steel	50	2·40	0·33	0·81
High-speed steel	150	18·02	0·90	0·40
Carboloy	1,000	—	6·00	6·25

These figures show the immense increase in speed in many manufacturing processes produced by the introduction of such an innovation

as carbide cutting tools, and the immense increase in power consumption which accompanies an increase in speed of working.

TRENDS IN MACHINE TOOL DESIGN

The trend of design in machine tools has been deeply influenced by the development of the new cutting materials, which have enabled the speeds and feeds of cutting machines to be increased so greatly. This has led to developments of speed and feed control. The range of speeds to be controlled is much wider, and the control of the feed-rate must be much finer.

These extensions in range and flexibility have been obtained especially by developments in hydraulic and electrical control. Today, the operator of a machine tool is becoming more like the driver at a motor-car, and less and less like the ancient blacksmith supplying his own power and skill.

Another direction of development has been in the design of the cutting edges of tools. The new carbide cutting materials have the limitation of low tensile strength. This has been particularly overcome by the introduction of negative instead of positive rake on the edge of the cutting tool.

The effect of slanting the cutting edge towards, instead of away from

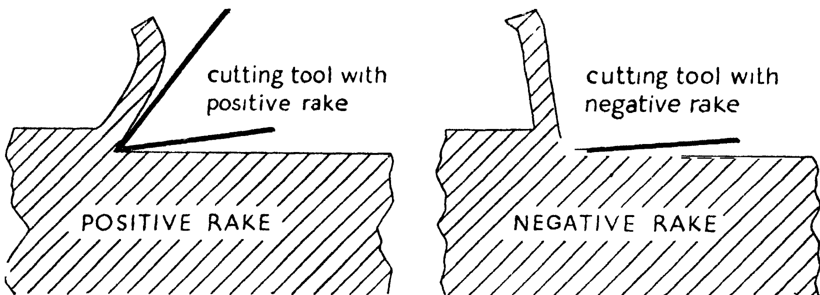
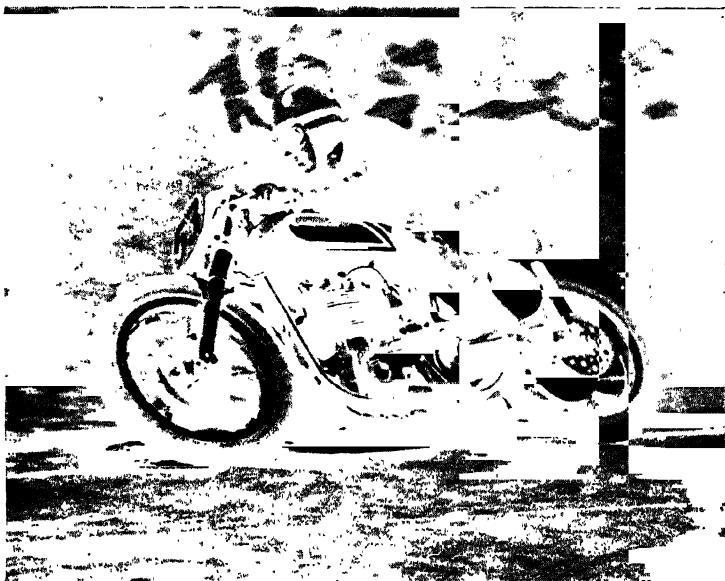


Figure 44. Positive and negative rake

the metal being machined is to convert the force from one of tension on the cutting edge to one of compression, which the tool can more easily withstand.

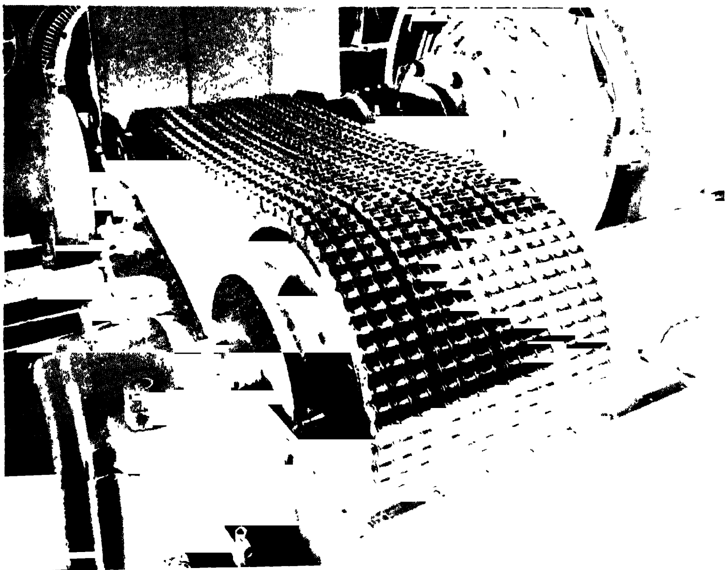
The negative-rake tool must be driven with more power than the conventional positive-rake tool. It works better with steel than with cast iron, owing to the abrasive action of the latter.

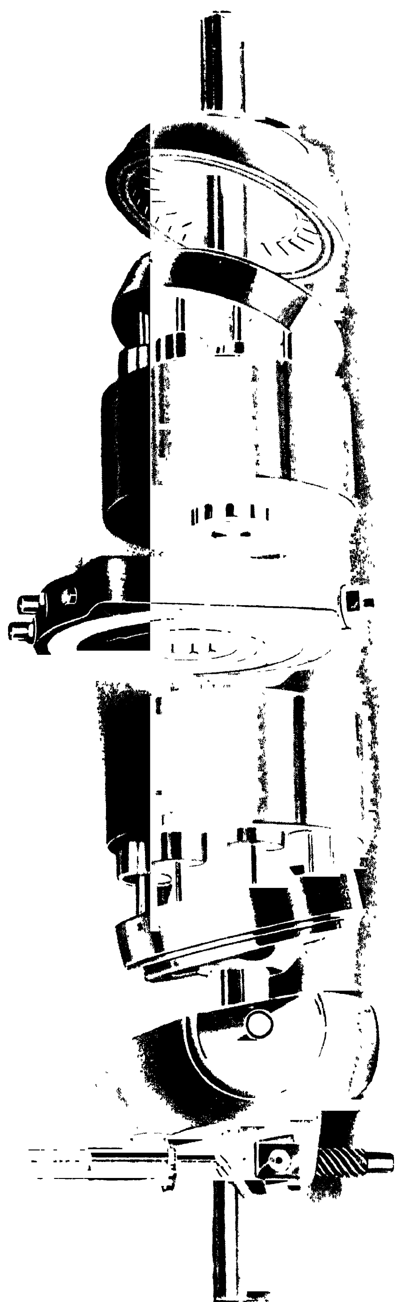
The load on a fast-cutting tool is less than on a slow-cutting tool. Negative-rake cutting takes only half the time, but requires 2½ times



(*Motor Cycle and Renold & Coventry Chain Co.*)

xx*ia*. Geoffrey Duke at speed on his 350 c.c. Norton in the Dutch Grand Prix, 1952. The two chains run entirely in the open with only drip-feed oiling. The pipe for oiling the primary chain can be seen just forward of the rider's boot





XXII. Variable speed oil transmission gear, dismantled to show construction

the driving power. The load on the machine elements is reduced by one-half owing to the transmission of the power at the higher running speed, which may be five times faster.

The design of machines with negative-rake cutters was resolved into the design of machines with faster running, but less heavily loaded parts.

An example of a modern negative-rake cutter is the Negraika, made by Messrs. Samuel Osborn & Co. Ltd., Sheffield.

The body of the cutter is made of carbon steel, with Osbornite sintered carbide tips brazed into the steel.

This cutter can give a finish accurate to 0·000030 in. on cast iron. The cutter runs dry, and is silent in operation. The maximum depth of cut is $\frac{3}{16}$ in. and the chipload is not less than 0·005 in. per tooth per revolution.

Cutters of this type produce parts so finely finished that they can be immediately assembled without any further working.

A diamond is superior to carbide as a cutting tool, as carbide is superior to steel. The tool life of a diamond compared with that of carbide is as 200 : 3.

The brittleness of diamonds limits their use to the machining of light alloys, non-ferrous metals, plastics, etc. A carbide cutter which runs 18·7 miles before regrinding under certain conditions, can be replaced by a diamond cutter which will run 1,250 miles before it requires relapping. A diamond cutter will turn 3,000 billiard balls before relapping, while a steel cutter generally does not produce one without regrinding.

Diamonds are not suitable for turning steel, owing to their brittleness. But they can run at almost unlimited cutting speeds, from 500–1,500 ft. per minute, for aluminium and magnesium alloys, and bronze.

Special machines, running at high speeds and with fine feeds, are required for taking advantage of diamond cutters. The spindle speeds may run from 3,000 r.p.m. downwards.

The wide range of speeds and feeds made possible by the new cutting materials and the general development of machine tools has increased the clumsiness of gear and lever mechanisms for operating them. Consequently, the infinitely flexible hydraulic mechanisms are being increasingly used. Besides their flexibility, they can be quickly reversed without giving a shock to the machine, they are quiet, have a long life and low power consumption, and are safe.

The essence of the hydraulic operation is the application of control by regulating the delivery of oil to a piston. This moves the saddle, or other part, without any screws, racks, gears, etc. Fluid power can be transmitted through long distances by pipes, and taken round corners and awkward places, where gears, belts and chains would be impossible.

Another development of machine-tool operation has arisen from the application of electronics. Here the control depends on a stream of electrons in some kind of electronic valve. Free electrons are virtually without inertia, from the engineering point of view, and infinitely flexible. It is this property which helps to make them such an effective and swift means of operation.

The General Electric Company, for example, supplies an electronic speed control device based on thyratron tubes. These control supply of direct current to the motor drive in the same way that the flow of water in a pipe can be controlled by a valve. The speed of the motor can be pre-set to any desired value. For a lathe, the speed can be fixed at any value from, say, 100 to 2,500 r.p.m.

In making radial aero-engines, the Ford Company found it necessary to use drills 10 in. long to bore certain holes in aluminium crankshafts. There were many drill breakages, so an electronic device was introduced which withdrew the drill automatically from the hole, if the torque became excessive.

The trend in evolution of machine tools is towards more and more automatization, with the ultimate end of the automatic factory.

Apart from size and accuracy the greatest advance has been made in automatic machine tools. The material is fed in at one end and a whole series of operations are performed upon it without any attention from the man. In fact so little attention is required that a man or boy can take charge of five or six machines. However complicated these may appear to the uninitiated they are in reality very simple. They have been developed step by step from the original machine in which every movement was effected by hand. First one motion was rendered automatic, then a second, then a third, and so on, until the machine can do everything but pick up material from the floor. Thus in some grinding machines the plate upon which the object would usually be fixed by bolts and slips is a pole of a magnet, and the movement of a switch holds the work in position as the carborundum wheel passes over the surface. In this way some half-dozen objects may be gripped at once, and when the process is complete they are instantaneously released by a single movement of the hand.

A common type of automatic machine is one in which steel rod is fed in at one end and is converted into small cheese-headed screws, with slotted heads, in its passage. The separate tools required in the process are mounted on small carriages which move up to the end of the rotating rod and retreat when they have done their work. As the last of these cuts off the screw it is seized by a pair of steel fingers and transferred to a vice which grips it firmly while a steel saw mounted on a carriage advances and cuts the groove in the head for the screwdriver.

THE TRANSPORT OF MATERIAL

Perhaps no part of modern works or factory equipment is more remarkable than that which transports the material from one place to another. All shops in which heavy articles are dealt with have an overhead travelling crane, which moves up and down and from side to side, picking up here and depositing there huge weights that a dozen men would be unable to move. While in most of these the object is slung by chains to a hook, the latter is sometimes replaced by a powerful magnet, which picks up a ton or more of iron as easily as a toy magnet picks up iron tacks. It is quite startling to see one of these magnets lowered on to a heap of pig iron and made to pick up a dozen or more of pigs by a slight movement of the crane-driver's arm.

One method adopted both in factories and yards is to employ an overhead railway with a single rail. From this is suspended by two wheels a small cage containing an electro-motor, a man, and a winch. The cage picks up material and conveys it expeditiously to its destination.

Where there is plenty of floor space travelling belts are frequently employed.

Broad, heavy belts or bands of this kind are used for all kinds of material—perhaps on the largest scale for coal and corn. In these cases they are usually called conveyors. The band is not always level, and often proceeds up and down hill, but some means has then to be taken to prevent the material slipping down. It often forms part of a machine. Thus in an ordinary threshing machine the corn falls from the ear on to a belt which is violently shaken from side to side, while a blast of air from a fan passes over in the opposite direction to that in which the corn is being conveyed. The shaking causes the lighter husk to rise to the surface, whence it is blown away, while the corn is carried forward on the belt and tipped into a sack. A similar method is used in gold-mining machinery. The crushed quartz, among which are fine particles of gold, is washed on to an india-rubber band which also has a shaking motion. The heavy gold remains on the belt while the coarser but lighter quartz is brought to the surface and washed away.

ELECTRIC WELDING

A neat process for joining two pieces of iron or steel, which has been in use to some extent since 1886, but has been greatly developed during recent years, is that of welding by electricity. The usual process as carried on in the shops is as follows: the two pieces to be joined are connected up with a source of electricity (from a dynamo or public supply acting through a transformer) giving a strong current at low voltage. The ends grasped in sliding holders are then pressed together,

and being rough they touch only at a few points. The resistance at the junction is therefore much greater than at other parts of the circuit, the ends are raised to the softening point, and an excellent joint is formed. A slight bulge round the joint, owing to the force employed in pressing the soft ends of the rods together, is removed by subsequent hammering, which is beneficial in other ways. This process was devised by Professor Elihu Thomson, and a current of from 50,000 to 100,000 amperes at from 1 to 5 volts is used. The use of massive clamps prevents any other portion of the apparatus than the bar under treatment being overheated.

A modified form of apparatus enables quite thin strips or rods—not more than $\frac{3}{4}$ in. diameter—to be welded; and copper, brass, and practically all metals and alloys can be joined in this way. In the case of iron and steel it is necessary to keep the temperature below that at which the metal fuses, and for this reason considerable pressure must be used. For other metals the pressure need only be sufficient to bring them into contact as the extreme ends fuse, when the current is immediately cut off.

There are, however, other methods which are useful not only in the workshop, but also in the shipyard and on outdoor repair work generally. In one a flame arc is formed between two inclined carbon poles and blown forward on to the joint to be welded as the ends of the carbons are moved along over the surface. Another method is to make the object to be patched or repaired one pole, and to move a single pole over the defective portion. In these cases a rod of soft iron is often used and small dabs of fused iron are plastered along the joint, and afterwards well hammered to render the joint solid.

The metal electrode process, while possessing many advantages, was not altogether free from objection, the most serious of which was the tendency of the molten metal to become oxidized. This was overcome by covering the pole with a flux which melts at the same temperature as the metal, and which flows over and protects the joint.

Electric welding is now very widely employed. Many parts of machinery are now built up by welding instead of casting. Welding is a much more flexible technique, and has greatly speeded up the production of construction in steel. Aeroplane frames and wings, electric cables, steel band saws, tyres for wheels, bicycle parts, steel tubing, coils of piping for refrigeration (see Chapter X) and many other articles are jointed by this process, in addition to repairs on railways, in shipyards, in boiler shops, and many other kinds of work.

CASTING AND WELDING BY THERMITE

Another portable process that has a very wide range of application is the use of thermite, though probably it belongs more particularly

to the foundry. It was invented by Goldschmidt, and depends upon the fact that when powdered aluminium is mixed with a metallic oxide and ignited, it burns with a very high temperature—about 3,500° C.—removing the oxygen from the metallic oxide and liberating the metal in a molten condition. As this temperature is more than sufficient to melt every known metal the process can be used to make small castings of the rarer or more refractory metals and alloys. For this purpose a quantity of powdered aluminium is mixed with the necessary proportion of the metallic oxide or oxides, in a crucible, and a fuse of some material which ignites more easily than aluminium, which requires a temperature of 700° C., is placed on the top. When the fuse is ignited the whole mass flares up, and in a minute or two the metal is ready for pouring.

This process has been largely used as well as the electric one for welding together the end of tramway rails. In an ordinary railway track it is necessary for each length of rail to be independent of and separated from the next one, by an amount which will allow for expansion in hot weather. But as the rails for electric tramways are used to convey the current, they must be in continuous metallic connection. Formerly this was accomplished by connecting each rail with the next one by a metal strip bolted on the side below the rail head. Rails are, however, less likely to buckle under climatic temperatures than was formerly supposed, and it is now the custom to weld the ends of the rails together. Besides improving the electrical connection, the noise and shaking of the wheels over the joints is reduced. For this purpose a small crucible containing the powdered aluminium and iron oxide is fixed on a tripod stand over the rail joint. The paving is removed at this point and a mould is made round the rails. The fuse is fixed, ignited, and in a minute or so after the flare a hinged bottom to the crucible is allowed to fall, and the metal pours into the mould below. The latter is afterwards broken away, and the protruding metal ground away to the level of the rail head.

OXYACETYLENE WELDING AND CUTTING

Striking as are the results of the processes described they are in some circumstances eclipsed by the introduction of the oxyacetylene blowpipe. Formerly the hottest flame obtainable in a blowpipe was produced by a mixture of oxygen and hydrogen, which gives a temperature of about 2,000° C. But hydrogen never was cheap, and acetylene is—at any rate relatively so. Moreover, a mixture of oxygen and acetylene produces a temperature of 2,400° C., and is therefore 20 per cent hotter than the oxyhydrogen flame. And when after Moissan's discoveries in connection with the electric furnace calcium carbide, which in contact with water generates acetylene, came to be manufactured in quantity,

engineers and metal workers availed themselves of the new process. For welding purposes the parts to be joined are heated with the flame and are then brought into contact and hammered. Or if a patch is being put on or corner joint made in thin sheet, the metal is heated and dabbed with the end of a thin soft-iron rod, much in the same way as the plumber uses a stick of solder, or any of us use a stick of sealing wax.

Nearly all the ordinary processes of welding can be carried out by this method, and a great many pieces of work which would be spoilt by being placed in the smith's fire are easily dealt with. Not only has it provided an alternative method of jointing in many well-established forms of construction, but it has aided in no uncertain way that enormous development of mechanical practice which has taken place during the last thirty years. In this and in other ways workshop practice is being revolutionized.

But if oxyacetylene welding is an example of progress, oxyacetylene cutting is a far more startling one. If a jet of oxygen gas is allowed to play upon red-hot iron, the metal burns in the gas with brilliant scintillations. The oxide which is formed melts at a lower temperature than the metal and is blown away almost as rapidly as it is formed. The most effective type of blow-pipe for this purpose is the concentric one illustrated in Plate XXIII*c*. From the diagrams it will be seen that the oxyacetylene flame is produced at the mouth of the space between the inner and outer tubes, and oxygen is blown through the middle of it. When such a jet is moved over the surface of sheet iron it cuts a hole clean through. The usual workshop methods for cutting are shearing and sawing. To the former there is a limit of thickness—more than 1½ in. is rarely attacked—and the latter is slow. If a large hole has to be made in the middle of a sheet of metal it must either be bored out or a number of holes drilled round the margin and the piece chipped out with hammer and chisel. These operations are carried out with far greater ease by the oxyacetylene jet, and with astonishing rapidity. An elliptical manhole—say 16 in. by 10 in.—in a 1-in. boiler plate only requires four or five minutes, and an armour plate 6 in. thick can be cut clean through at the rate of a yard in ten minutes. Plate XXIV shows a large thick rectangular plate being cut to semicircular form by a jet mounted on the end of a radial arm.

The extreme portability of the apparatus—the acetylene and oxygen are contained in steel cylinders—renders it of particular value for repair work. For instance, a large ship damaged in a collision can be fitted with a new bow in two or three weeks.

QUALITY CONTROL

When goods were manufactured in small factories, before the days of advanced mechanization, the quality of the goods produced depended on the skill of the craftsman rather than on equipment. Responsibility for quality rested on the foreman who directly supervised the work. The growth of factories and the extension of equipment with machine tools, accompanied by the wider and wider utilization of unskilled workers, extended the range of the supervision of quality beyond that of the shop foreman. The production of the product became the outcome of specialized departments. The designing engineers specified the quality, the laboratory set the standards of quality, production and manufacturing departments made the product of the specified quality, and the planning department worked out the procedures for production. Finally, the product had to pass inspection and tests.

All of these specialized departments were concerned with the quality of the product, but no one of them exclusively. The control of them was haphazard.

It gradually became evident that the highly mechanized modern industry, directed towards mass-production, was liable to produce large quantities of unsatisfactory goods, if no appropriate system of control of quality in the new situation was devised.

As the ramifications of control of quality became wider, and spread over more and more departments, the responsibility for it moved farther and farther from the individual craftsman, to the foreman, to the inspector, and more and more to management.

The parts of modern machines, such as motor-car engines and telephones, require to be made very precisely if they are to function properly, and be interchangeable.

Fifty years ago, the precision quality of many products could be determined sufficiently accurately with a carpenter's measuring scale, but today, tolerances of one ten-thousandth of an inch, or of one-hundredth of a volt, are commonplace.

In addition to the development of instruments for making measurements of precision more accurate, there has been a development of techniques for enabling higher standards of precision to be attained in the goods produced.

One of the most striking of these is the application of statistics to quality control. This began to make progress about the time of the First World War, and was developed especially by W. A. Shewart of the Bell Telephone Company in the production of telephone equipment. But it did not make spectacular progress until stimulated by the enormous production demands of the Second World War. In the United States, for example, 7,500 men and women were given special university

courses on methods of statistical quality control. These methods can be applied to virtually any product, to radios, electric motors, turbines, screws, bricks, bread, chocolates, drugs, beer, etc.

During the Second World War a manufacturer of electrical equipment for aircraft found at the beginning of his production that the cost of his losses owing to poor quality was as much as 35 per cent to 40 per cent of his expenditure on labour. The biggest part of the cost, 30 per cent, was due to the very large inspection department necessary to sort out the products and allow only those up to standard to go to the consumer.

The introduction of quality control methods enabled the losses to be reduced by 50 per cent, and the cost of inspection by 33 per cent, within nine months. Besides these savings, several possibilities for improvements in design were revealed, a number of production hold-ups eliminated, and the morale of the workers raised.

Three of the chief ways in which quality control is carried out are by study of frequency distribution, control charts, and sampling. Frequency distribution records the number of times a given size or quality characteristic occurs in a sample of the product. It can be made to show the average quality, the spread of this quality, and its comparison with the specification.

The control chart records hourly or daily quality characteristics in a product. It reveals the degree of a variation known to occur, and variations whose existence was not suspected. Study of the chart may lead to the discovery of the cause of the variation, and its cure.

The technique of sampling is used to test the quality of finished products. The application of appropriate methods of analysis indicates the degree of exactitude of the results of sampling conducted on various scales and in different ways.

Sampling can, under some conditions, lead to more reliable results than 100 per cent inspecting, i.e. when every article is individually tested by an inspector. A human being gets tired, and after he or she has tested, say, 5,000 articles during the first three-quarters of the shift, his or her standard of accuracy may go down through fatigue. If the batch during the first three-quarters of the shift has been a good one, there is a psychological tendency to assume that the last quarter will be good, too, and not to bother about it.

If the inspecting is done automatically by machine gauges, this also may fail to work properly, for machines fail as well as human beings.

T. G. W. Boxall has given an interesting illustration of the use of control charts to the manufacture of bricks. The London Brick Company makes 1,700,000,000 bricks a year at its twenty-four Fletton brickworks. The clay all comes from the same stratum and the processes of manufacture are largely standardized, yet there are considerable

variations, e.g. in size, in the products. Clearly, they could not individually inspect 1,700,000,000 bricks in order to check these differences.

They accordingly arranged for six bricks chosen at random from each of two kilns at each factory on each working day (each kiln burnt 40,000 bricks a day), to be measured to within $\frac{1}{16}$th of an inch. The figures were recorded for a year on a chart. All the average lengths fall within the standard, but are rather above the mean length (8·75 in.). Thus, if the press mould boxes at Works D could be slightly shortened, the risk of bricks being rejected because of overlength would be reduced. A small increase in the width of the box, of the feeding mechanism for thickness, would reduce the risk of rejection for these dimensions.

At Works C, the clay has variable shrinkage characteristics. During the weeks 2nd January to 27th February, and between 19th June and 14th August, the excavating machine collected clay from a place in the pit where it has an exceptionally big shrinkage characteristic. The effect of the shrinkage is less on the thickness than on the width or length, because thickness can be more easily controlled by feeding.

Thus the control chart has given a clearer picture of the nature of the material coming from the pit.

Similar studies are being made of crushing strength, weight, and absorption, the quality of bricks made by different machines and burnt in different kilns, and the results of different firing methods.

The information about the performance of plant under normal working conditions, gained from small samples, is much more useful than that given by measurement of total output.

B. Moorhouse of Messrs. Rowntree & Co. Ltd. has described how control charts were used to study a problem in the production of a moulded chocolate block. Its 'centre' showed more variation in weight than was desirable. Systematic studies were made of the moulds, the position of the cake within the moulds, and variance in day-to-day runs. Testing of the moulds showed that 10 per cent were inaccurate. These were eliminated.

Variation of the position of the cake in the mould was reduced by using a more flexible steel blade for trimming off the surplus filling.

Variation between runs showed that 'centres' manufactured to a given thickness were less variable than those made to a given weight, i.e. thickness was more important than weight.

Control charts reveal the influence on quality of the time of day, lunch and tea-break, starting and stopping work, the effect of fresh batches of ingredients, change in the operator, re-setting of the machine, etc.

The way in which the components of a machine are assembled may effect big savings of time and labour. Assembly processes include random or interchangeable assembly, semi-random assembly, simple

selective assembly, and multiple selective assembly. The methods apply not only to factory operations. A man who wears trousers is an assembly, made by putting together the man and the trousers. In ready-made tailors' shops men are provided with trousers made by selective assembly.

The putting-together of the parts of an article can be mathematically analysed. Such an analysis may show, for instance, that it may be advantageous to put more than two components together at a time.

When the best method of assembly has been worked out, the production engineer can plan the most efficient design of assembly bench, and disposition of parts, for the method chosen.

Quality control reveals the machine and the worker who are too accurate for their job, as well as those that are not accurate enough. Suppose a component is being made with a nominal dimension of 1·550 in., with a drawing tolerance of $\pm$ 0·004 in. Suppose the average range of 25 samples of four is found to be 0·001 in. and their grand mean to be 1·549 in. Now it can be shown that the components will come within the Drawing Tolerance of $\pm$ 0·004 in., if the average range of the samples is not more than 0·0026 in. Thus the machine is unnecessarily accurate, and the toolsetter is being asked to keep to much closer limits than is necessary, in both cases an extensive waste.

Quality control analysis will indicate to the producer what degree of accuracy is most economical, whether it is cheaper to make objects of medium precision and reject a large number of defectives, or whether more expensive, more precise components, with few defectives, will on the whole be more economical. The application of analysis in the manufacture of articles such as bullets and shells, the parts of guns, and any articles which are produced in enormous quantities, can lead to spectacular savings in production costs.

The development of quality control gives a deeper understanding of the relatedness of all productions, and of innumerable factors both in the human operations of productive processes, and in the machines and materials utilized in them.

VIII

FOUNDRY AND FORGE

THE production of steel is now much greater than that of pig-iron, a great change since the beginning of the century, which shows the advance in using a more complicated basic material in the place of an older and simpler one. The comparison of the steel and pig-iron production figures for the world, for the United States, and for the United Kingdom, for 1951 and 1900, are shown in the table:

	1951	1900
STEEL		
	tons	tons
World	206,530,000	27,660,000
United States	93,930,000	10,190,000
United Kingdom	15,638,000	4,900,000
PIG-IRON		
	1951	*1900*
	tons	tons
World	144,790,700	39,810,000
United States	64,690,000	13,790,000
United Kingdom	9,670,000	8,960,000

The change in the balance of steel and iron production, especially in the United Kingdom, as compared with that in the world, and in the United States of America, is very striking.

THE MANUFACTURE OF IRON

During the last fifty years the changes which have taken place in the manufacture of iron and steel have been mainly in the direction of improvements in quality, increase of yield, and economy of fuel. In order to understand how these have been effected it will be necessary to recall briefly how iron is reduced from its ore. From very early times, until the middle of the eighteenth century, iron ores were smelted in masonry furnaces with charcoal, and the necessary temperature was

attained by blowing in air with a bellows—often worked by a water-wheel. After this period the use of water for blowing gave way to the steam-engine, which became a satisfactory source of power in the hands of James Watt in 1769. Coke began to replace charcoal in 1735.

The ores of iron are usually oxide of iron mixed with *gangue* or earthy matter. The processes are rather complicated, and several reactions between the air, oxide, earthy matter, and fuel proceed simultaneously in different parts of the furnace. Limestone is added to form with the gangue an easily fusible slag, which floats on the surface of the molten metal. The slag is tapped off occasionally and is conveyed to the slag tip—some varieties are used for repairing roads. The metal is run into sand moulds about 3 ft. long, 4 in. wide, and 4 in. deep, and the resulting castings are called pig iron. A supply of ore, fuel, and flux (limestone) is fed in continuously at the top of the furnace, and iron may be produced daily for months or years.

Greater economy was secured by the invention of Neilson in 1829, by which the air was heated before being blown into the furnace. For over thirty years this air required a separate supply of fuel to raise the temperature of the iron pipes through which it was passed. In 1863 Sir William Siemens introduced the regenerative principle by which the hot gases from the furnace were led into one of two brick chambers filled with bricks so arranged as to leave open spaces or *chequers*. When this chamber was hot the gases were diverted through the other, and the air from the blowing engine was passed through the hot one. The chambers were therefore engaged alternately in storing up the heat and giving it up again to the blast.

THE ECONOMY OF FUEL

Further economy in the production of iron has been effected in two ways. One is an additional method of utilizing the hot gases from the top of the furnace. The following table shows their composition in two cases—where coke and raw coal are being used:

	Coke	*Raw Coal*
	%	%
Carbon monoxide (CO)	25	28·0
Carbon dioxide (CO_2)	12	8·6
Nitrogen (N)	59	53·5
Hydrogen (H)	2	5·5
Methane or Marsh-gas (CH_2)	2	4·4

The fuel most generally used is coke, but raw coal is employed in the west of Scotland, and a mixture of coke and raw coal in South Staffordshire. Charcoal, the original fuel, is still used in North America,

Sweden, and Styria, where timber is plentiful; the gases evolved have a similar composition to those obtained from coke. In all cases there is a sufficient proportion of carbon monoxide, hydrogen, and methane to render the mixture inflammable. For each ton of coal charged into the furnace 130,000 cubic feet of gas are produced, which provides a vast source of power. This is used as a fuel in gas-engines, and as a raw material of chemical industry.

A further supply of gas is obtainable from the coke ovens. In this case, as well as where raw coal is used in the blast-furnace, the tar and ammonia, which are valuable by-products, are collected and utilized. The ammonia is converted into ammonium sulphate and sold as an artificial fertilizer. The tar is distilled and used for oil fuel, disinfectants, and other purposes in the same way as the tar from town gasworks.

A more recent economy relates to the removal of moisture from the blast. Ordinary air invariably contains vapour water and the amount varies from day to day. Assuming an ounce of water in every 50 cubic feet, and a blast of 40,000 cubic feet per minute, the amount of moisture entering the furnace would be 300 gallons per hour! While the presence of even the minimum quantity of water in the air may be objectionable, the variation is still more so, because it causes the furnace to work irregularly and renders it difficult to secure a uniform quality of iron.

THE NATURE OF STEEL

Iron exhibits a marked variation in properties according to the amount of carbon it contains. Pure iron is a chemical curiosity, produced in a very small quantity in the laboratory for the purpose of research. The chief difficulty of obtaining it is the readiness with which it combines with carbon at the temperature of a furnace—in fact, carbon permeates iron even below its melting-point. It is this property of combining with carbon that gives the metal its wide range of utility. So long as the percentage of carbon is small the iron is soft and easily bent, and when two pieces are made hot and then pressed together they unite—the process is known as *welding*. It melts at a very high temperature (about 1,600° C.) and passes through a pasty condition in which it can be rolled, beaten, or pressed into a variety of forms.

If the percentage of carbon is increased the metal becomes harder, stronger, and more elastic. With a still higher percentage it becomes more brittle and less tough, and the melting-point is lowered, so that it becomes liquid at about 1,100° C. Iron containing less than 0·1 per cent of carbon is called wrought iron, with from 0·1 per cent to 2·5 per cent it is called steel, and with more than 2·5 per cent it is called cast iron.

Cast iron is classified according to the fracture and is termed white, grey, or mottled. The grey or mottled appearance is due to the

separation of carbon in the form of graphite. It is fairly elastic without possessing any great tensile strength and easy to work with machine or hand tools. But it melts suddenly and cannot be forged or rolled.

Leaving out for a moment the properties of steel it is evident that here are two varieties of the same metal, differing ostensibly only in the carbon content, which are adapted to a wide range of workmanship and purpose. If tensile strength is required, wrought iron can be used, for although the cost is high there are few shapes which cannot be produced by the smith. But if tensile strength is relatively unimportant there is practically no form which cannot be obtained by moulding. In all cases involving intricacy of outline or hollow spaces, casting is a far cheaper process than forging. Moreover, since the addition or subtraction of carbon converts the one into the other, an article can be made by the cheaper process and then converted into wrought iron by removal of the carbon, a removal which can be effected below the temperature of fusion.

In this process the castings are packed in iron boxes with hæmatite iron ore (Fe_4O_3) and heated in a furnace for from five to twelve days. The oxygen in the hæmatite converts the carbon of the castings into carbon monoxide, which passes away, and the castings are found to have the appearance of wrought iron, without, however, the fibrous structure and consequent strength which is induced by rolling. Many parts of agricultural implements are made of so-called *malleable* castings.

Now consider steel. With all percentages of carbon it has a higher tensile strength and is more elastic than wrought iron; and it is always less brittle than cast iron. It can be forged and welded, but the process is more difficult as the percentage of carbon rises. It can be melted and cast, but with more difficulty as the percentage of carbon decreases. In these respects it resembles both wrought and cast iron, but it possesses one property which distinguishes it from either. If it is raised to a high temperature and cooled quickly it becomes intensely hard. Moreover, if it is heated again to a lower temperature and then cooled quickly a degree of hardness is obtained which depends upon the temperature of the second heating. This process is called *tempering*, and it is the fact that steel can be tempered which makes it so useful for tools, because the necessary degree of hardness can be obtained without undesirable brittleness.

It may fairly be said that while its cheapness and wide range of application have, apart from its inherent qualities, retained cast iron in favour for many purposes, the last fifty years have seen the replacement to a very large extent of wrought iron by steel. It was Sir Henry Bessemer who first showed how steel could be produced quickly and cheaply. It consists essentially in burning out the carbon and other

impurities in cast iron by forcing air through the molten metal and then adding sufficient spiegeleisen (an alloy of manganese and iron with a high percentage of carbon) to produce steel of the desired quality.

In recent years the proportion of steel manufactured by the Siemens-Martin process has increased, and is generally preferred. A longer time is required, but for that reason the process can be more closely watched, and any desired grade can be obtained with greater certainty.

There are two other processes for the manufacture of high-class tool steels. One—the *cementation* process—is very similar to that already described for the production of malleable castings. But in this case it is the addition and not the removal of carbon which is effected. A pure variety of Swedish iron is packed in boxes with charcoal and heated for from eight to eleven days at a temperature of 1,000° C. When unpacked the bars have a blistered appearance—hence the name *blister steel.* They are broken and sorted by men who have learned to distinguish the character of the metal from the fracture, then reheated in piles and hammered into bars. It should be observed that the absorption of carbon has been effected at a temperature *below* the melting-point of the metal.

The length of time required for the process just described is leading to its disuse, and the next process, by which *crucible cast* steel is made, is much quicker. Wrought iron is mixed with charcoal and melted in a fireclay crucible. In the course of a few hours—usually about four—the iron will have dissolved the carbon, and can be cast into moulds. The ingots can then be rolled or pressed into the desired form. Much of the special steel which is now so important is made by melting the ingredients in an electric furnace as described in Chapter IX.

Many investigations have been undertaken to ascertain the relation between chemical composition, internal structure, and mechanical properties of iron and steel. The fact that steel of the same composition can exist in varying degrees of hardness shows that the percentage of carbon alone is insufficient to determine its properties, and that much depends upon its thermal history, i.e. to what temperature it has been heated and how it has been cooled.

Let us first consider the information that can be obtained from chemical analysis. Grey and mottled cast iron consist of a white, hard substance mixed with graphite. When the metal is dissolved in hydrochloric acid this graphite is unaltered, but the gas which comes off is not pure hydrogen, but hydrogen containing some hydrocarbons, or bodies consisting of hydrogen and carbon. If cast iron containing not too much carbon is melted and run into metal moulds it becomes 'chilled' and then consists of white cast iron. On dissolving this in hydrochloric acid there is no residue of graphite, and the carbon is all evolved in the form of hydrocarbon gas. Hydrochloric acid has no action on free carbon,

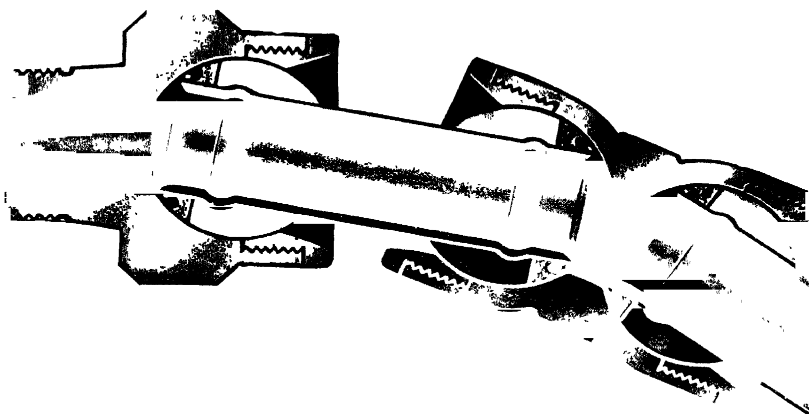
and could only give the hydrocarbon gas if the carbon were present in the form of a compound with the iron. It is evident, therefore, that there are two forms in which carbon exists in cast iron—free and combined. Moreover, as the hardening property of steel is intimately connected with the presence of carbon, it is evident that when the percentage of it lies between certain limits there is some special variety of compound which is still to be explained.

Our knowledge of the structure and constitution of metals and alloys has been enormously extended in recent years by the aid of the microscope, X-rays, etc. The surface of the metal is polished—a process which causes the harder constituents to stand out in relief; or it is treated with acids or other reagents which attack and destroy some portions and reveal those which were otherwise indistinguishable. As different constituents become capable of identification names have been given to them, and, though the whole question is still in the throes of acute controversy, a few of the more firmly established facts and theories may be given.

It has been known for many years that when a piece of iron is allowed to cool down from 1,000° C. or thereabouts there is a point at which cooling suddenly ceases. The wire, rod, or strip glows brightly and undergoes a change of volume. Below this point the metal is magnetic; above it is non-magnetic. If the metal is heated, e.g. by an electric current, instead of cooled, the same phenomena are observed. The change was explained by saying that iron existed in two forms, one stable only at a bright red heat and the other at ordinary temperatures, and that the point of recalescence, as it is called, was the point at which the one became converted wholly into the other. More careful study with improved instruments for measuring temperature has shown that there are two points of recalescence, and it is concluded, therefore, that there are *three* forms of iron—*allotropic* forms is the scientific term. These are called α-iron or ferrite, β-iron, and γ-iron.

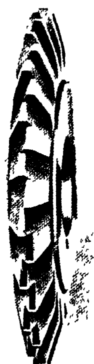
The readiness with which carbon dissolves in iron and the marked effect which it has on the properties suggest that one or more compounds of the two elements are formed. At least one of these is recognized both by chemical analysis and under the microscope. It has the formula Fe_3C, and has been given the distinguishing name of *cementite*. A solid solution of cementite in γ-iron is called *austenite*; a similar solid solution of cementite in α-iron is called *martensite*. During slow cooling ferrite and cementite separate in microscopic layers and the hardness of the latter gives rise to a pearly appearance on polishing. Hence the name *pearlite* for the mixture. More rapid cooling causes separation in granules, and the mixture is then termed *sorbite*.

The appearances under the microscope are illustrated in Plates XXV*a* and *b*. White cast iron invariably contains crystals of austenite which

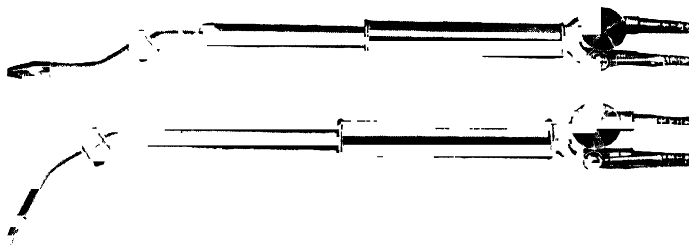


XXIII*a*. Flex-steel pipe for wave transmission

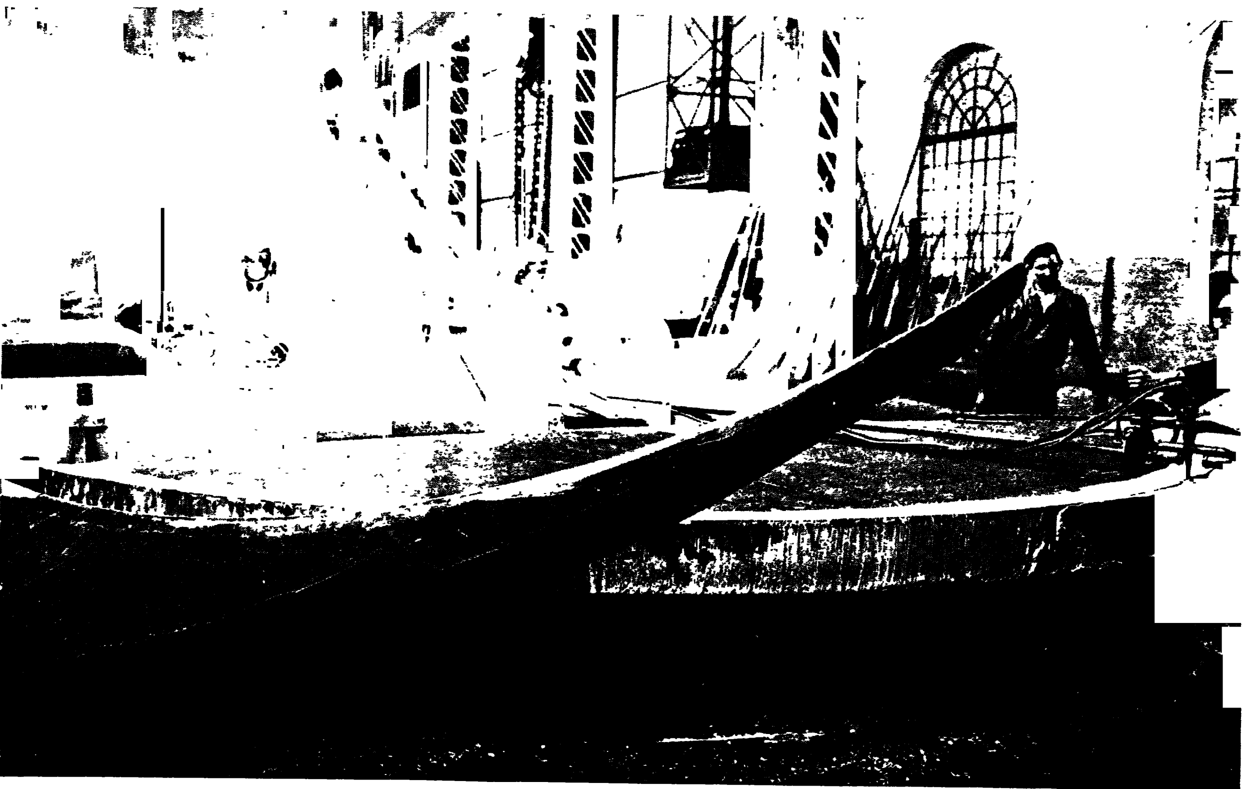




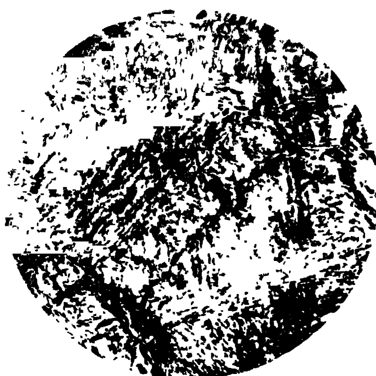
XXIII*b*. Acme thread cutter



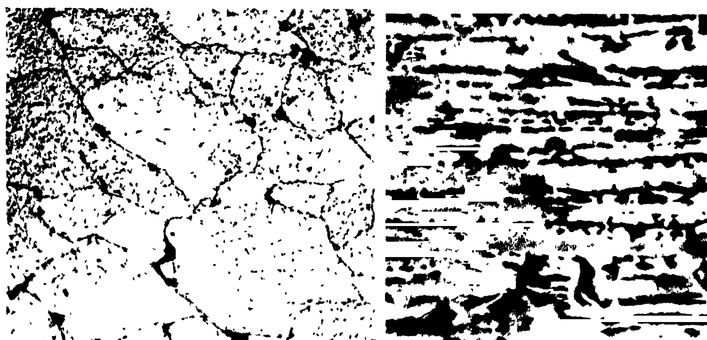
XXIII*c*. Concentric blowpipe for oxyacetylene cutting



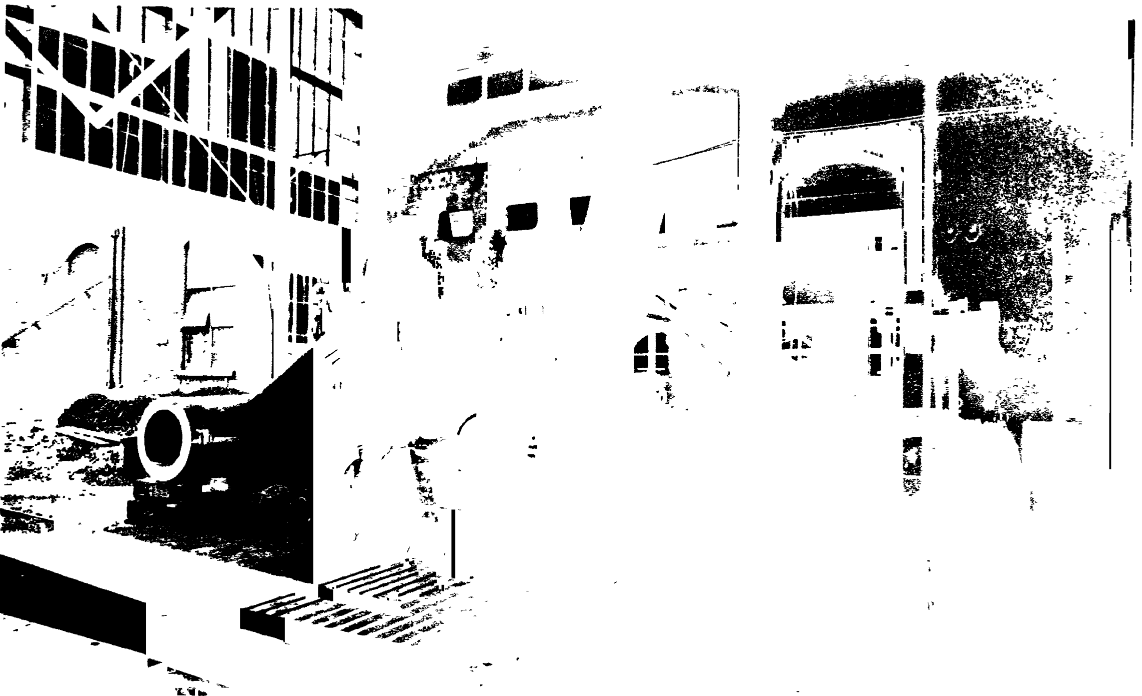
XXIV. Cutting a semi-circular plate with an oxyacetylene blowpipe



XXV*a*. Nearly pure iron. The fine dark lines show the outline of the crystals, and the specks are slag



XXV*b*. Mild steel: Ferrite (*light*) and Pearlite (*dark*), showing the direction of rolling



XXVI. After propeller brackets of the White Star Line *Britannic*. Two castings; total weight about 100 tons

have become changed into pearlite on cooling, though if the percentage of carbon is more than 4·3 crystals of cementite will be formed independently. Grey cast iron contains graphite, pearlite, and either ferrite or cementite according as the carbon is higher or lower than the amount required to form austenite. The development of X-ray analysis has enabled the scientist to probe into the inner structure of steel and other metals. This has given further insight into the known properties of metals, and modern quantum theory has been able to explain some of the observed facts. But metallurgy still depends basically on practice and extensive experiment.

The theory of the constitution of steel has been the subject of an enormous amount of controversy, but whatever their explanation, the facts which have been discovered have been of incalculable value in enabling the steel-maker and the engineer to understand and make allowance for the peculiarities of the material upon which so much depends. The safety of such a structure as the Forth Bridge—which even today stands as one of the great engineering achievements of the world—rests not only upon the proportions of the different members and upon the number, distribution, and soundness of the rivets, but to an equal extent upon the microscopic structure of the steel. In the days when it was built this was unknown or but dimly recognized, and the engineers had to depend upon the behaviour of test pieces and to take care to put in girders, ties, and struts not large enough as they felt, but too large. Even chemical analysis—now supplemented extensively by the microscope—was not in use in all works. Up to the beginning of the present century there were steel works in which no chemist was regularly employed, and in which the simple necessary tests were carried out by workmen under the supervision of the manager, but with very little knowledge of what they were doing. The temperature of the furnaces, now known to be so important, was never measured. Today steel-makers know and control the temperatures to a nicety. And when these furnaces have yielded up their burden, samples of the steel are bent, stretched, and broken in the testing machine; analysed in the chemical laboratory; etched or polished, and examined under the microscope, which reveals their innermost secrets; and before the metal goes to the engineer to be entrusted with delicate duty in some machine, or to play its part in a great structure, its every peculiarity is known. The very molecules have told their tale!

SPECIAL STEELS

The properties of steel are profoundly modified by the presence of other elements than carbon, and by the actual amount of each. In some cases the effect is good, in others bad, and during the last fifty years

an enormous amount of work has been done in investigating the effects. The chief properties of steel which are important from an engineering point of view are tenacity, ductility, and hardness. The first of these determines the resistance to breakage by pulling at each end, the second determines the ease with which it can be rolled into plates, drawn into wire or bent, and the third determines the resistance to wear by rubbing surfaces. A fourth property, at present not fully investigated, is the resistance to corrosion by air, water, and other fluids.

One of the earliest substances to be alloyed with iron was manganese. With low carbon steels a small amount increases tenacity and decreases ductility. The axles and tyres of wheels may have up to 1 per cent but a steel containing even 0·6 per cent would be quite unsuitable for boilers and structural work. In steels containing more carbon the percentage should not rise above 0·3. This effect continues with all types of steel until with 5 per cent to 7 per cent of manganese and 0·5 per cent carbon the metal is brittle. The late Sir Robert Hadfield has shown, as a result of an investigation which occupied ten years, that a cast-steel bar containing from 8 per cent to 20 per cent of manganese can be bent considerably without fracture, and his manganese steel is useful, but very hard and difficult to work in the cold. It is extensively employed for the points of railways and in other cases where an extremely hard, and yet not brittle, metal is required. Hadfield's development of manganese steel founded the alloy steel industry.

Perhaps the most widely used alloys of steel are those containing chromium, nickel, and tungsten. Chromium and nickel both increase the toughness, and are used largely for armour plate and projectiles. Tungsten steel for tools was introduced by Mushet in the middle of last century. It is a self-hardening steel which does not require to be suddenly quenched in order to temper it. The use of these metals has been extended in recent years by improved processes of manufacture. Thus Dr. Ludwig Mond's processes for the production of nickel led to a considerable increase in the supply of that metal. But the most remarkable progress owes its origin to Moissan's work with the electric furnace (Chapter IX). Not only chromium and tungsten, but titanium, molybdenum, and vanadium were then obtained for the first time in quantity and in a high degree of purity, and the electric furnace is now very generally used for preparing rich alloys of these elements with iron to add to steel.

Tungsten or molybdenum is contained in the new high-speed tool steel. The original Mushet steel, which contained tungsten and was self-hardening, would cut hard steel at the rate of 8 to 10 ft. per minute, and soft steel at the rate of 10 to 15 ft. per minute for heavy cuts, and 20 to 25 ft. per minute for light finishing cuts. Similarly a milling tool would cut at 30 to 40 ft. per minute. In 1900 Messrs. Taylor and White

discovered steels that would work satisfactorily at a low red heat. It has generally been supposed that if Mushet steel was heated above cherry redness (815° C. to 845° C.) it was spoiled. But they found that if it was heated to the point when the metal began to crumble when touched (1,040° C. to 1,100° C.), and then allowed to cool steadily, its hardness and toughness are increased to an extraordinary degree. There are now a number of varieties on the market, and, curiously, some of them are not steel in the proper sense of the word because they contain no iron. In one, nickel is the principal constituent. But so long as a tool will do the work that is required of it, no one will quarrel about the name.

Of other substances used for alloying with steel, vanadium and silicon may be mentioned. The former is contained in some of the tool steels to which reference has been made. As it combines with nitrogen to form a nitrate it is possible that its value lies in the removal of dissolved gases and the production of an ingot free from minute cavities. For example, titanium, which is an element of similar properties, is sometimes added to molten iron in order to produce especially close-grained and sound castings. It is also used in steel manufacture, but does not appear to have such a powerful effect as vanadium, 0·5 per cent of which, in a particular case, increased the tenacity by over 50 per cent steel, with 0·35 per cent of silicon as used for springs.

One of the most important discoveries was that of stainless steel by H. Brearley in 1912, in the Brown-Firth Research Laboratories, Sheffield. An investigation carried out in connection with erosion in gun barrels resulted in the production of a chromium steel which was unaffected by atmospheric moisture. Highly polished pieces exposed to the air of the laboratory for several weeks retained their brightness under conditions in which ordinary steel rapidly became rusty. The alloy contains from 12 per cent to 14 per cent of chromium and about 0·3 per cent of carbon, and some difficulties had to be overcome before it could be hardened and worked successfully in the forge. A much higher temperature is required for tempering. It can be hardened by heating it to between 950° C. and 1,000° C. and quenching it in oil or water, and softened by heating to between 850° C. and 870° C., and allowing to cool very slowly. For machining it is in its best condition when heated to between 750° C. and 800° C. and allowed to cool in air. These facts illustrate not only the delicacy of the operations and accuracy of the measurements in a modern steel-works, but the amount of experimental work which must have been necessary in order to secure the highest utility from the material.

Stainless steel is used for cutlery, surgical instruments, springs, dental instruments, golf-club heads, finger-plates for doors, furnishings for stoves and grates, hollow-ware, scientific apparatus, and motor-car

parts. It is also applied to the blades of steam turbines—not so much for its freedom from rusting as for its resistance to erosion.

THE EFFECT OF ALLOY STEELS

The development of alloy steels has contributed enormously to the progress of the metal-using industries of our technological civilization. When manganese steel was introduced in 1888, and nickel steel a year later, the world production of steel was less than 10,000,000 tons. The development of alloy steels, due to Robert Hadfield's introduction of high manganese steel, made possible the working and utilization of greatly increased quantities of steel. In 1951, the United Kingdom production of alloy steel castings was 969,000 tons, i.e. less than one-fifteenth of the total United Kingdom steel production. But it is the tools made from the small fraction of alloy steels which enables the mass of steel as a whole to be worked and utilized.

The world's enormous total annual production of 206,000,000 tons of steel would scarcely be usable without the special tool steels which enable it to be worked. Alloy steels have, as it were, a strategic position, and the ratio of alloy steel to total steel production has significance, besides the size of the total figure of steel production.

Alloy steel provides the jaws for ore-crushers, the teeth of bits for rock-drilling, and essential parts in modern motor-car engines, and in jet engines for aircraft. These typical modern machines would scarcely be possible without alloy steels.

The vast range of alloy steels developed since their introduction sixty years ago have made the variety of modern machinery possible.

Simple carbon non-alloy steel is available in a wide range of qualities. Steel with a low carbon content, such as is used in the bodies of motor-cars, is soft and ductile. The high carbon steels, of which files are made, are hard and brittle. Different combinations of hardness, strength and ductility are obtained by varying the content of carbon, and by heat treatment. A high carbon steel can be made about as hard as any alloy steel, and a low carbon steel about as tough, but a combination of hardness and toughness can be obtained, especially in large masses of metal, only by heat-treating an alloy steel.

The effect of adding other metals or elements to form alloys is to make the steel more responsive to heat treatment, and thus to obtain new combinations of desirable properties. The addition of certain metals may produce new properties, such as the resistance to corrosion conferred by chromium, or the retention of hardness at high temperatures, conferred by tungsten.

The present British conventional definition of an alloy steel is one 'containing 0·40 per cent or more of chromium or nickel, 0·10 per cent

or more of molybdenum, tungsten or vanadium or 10 per cent or more of manganese'. This by no means covers all those alloying elements in use. For instance, cobalt, columbium and titanium are used extensively, and the common constituents of steel, such as silicon, sulphur and phosphorus, may be increased for some purposes.

Alloy steels were first made in small crucibles, as their composition and properties required exact control. Then they were made in electric furnaces. Later on, the open-hearth technique as used in ordinary larger scale steel production was adapted for steel alloy production, and in ordinary times the electric process and the open-hearth process are about equally important.

In the United Kingdom, about 170 firms are engaged in producing alloy steels. The production in 1949 of the chief steel alloys was, in thousands of tons:

Nickel	72·9
Nickel-chrome	64·6
Nickel chrome molybdenum	130·5
Chrome molybdenum	49·4
Manganese molybdenum	88·1
Chrome vanadium	6·2
Carbon chrome	114·2
Corrosion and heat resisting	74·0
Tungsten high-speed steel	14·5
Other qualities	90·8

The main users of these were the engineering and aircraft industries (two-fifths), the motor industry, including agricultural tractors and machines (two-fifths), export (one-eighth), and the rest to miscellaneous consumers. Only about one-quarter of total deliveries of every kind of steel went to the engineering and aircraft industries, and only about one-tenth was used in the motor vehicle and agricultural machinery industries.

The effect of an ingredient in an alloy depends on the amount, and the subsequent heat treatment. Speaking roughly, small quantities of chromium, up to 1½ per cent, increase hardenability, tensile strength and ductility. It is the sole alloying element in steel for ball bearings, which contains 1–1½ per cent. Stainless steel for cutlery contains about 13 per cent, but that used in machinery, which must be more ductile and resistant to a wider range of corrosive substances, contains 18 per cent, with 8 per cent of nickel.

Cobalt is used for producing resistance to high temperature. In tool steel there is 5–10 per cent. In magnet steels the proportion may be 40 per cent. This greatly increases the coercive force.

Nickel is used to increase tensile strength and toughness. Tungsten is the most important constituent of high-speed steel. In some varieties chromium, or vanadium, or other metals are added in small amounts.

Molybdenum gives stainless steel of the 18 per cent chromium, 8 per cent nickel type resistance to sulphuric and other acids. Vanadium increases hardenability and other important qualities.

Columbium, tantalum and titanium prevent 'weld-decay' in stainless steel of the chromium-nickel type.

The production of the ores of some of these metals is very unevenly distributed. More than 80 per cent of the world production of cobalt comes from the Belgian Congo and Northern Rhodesia copper mines. Eighty-five per cent of the world's production of nickel comes from Northern Ontario. Ninety-five per cent of the world's production of columbium comes from Nigeria. The U.S.S.R. is by far the largest producer of manganese, and the largest producer of chromium.

FORGING

Since steel can either be forged or cast and run directly into mould from the furnace in which it is prepared, there is little to say about the latter process. For small articles of simple form, cast steel is an admirable material; but there are two difficulties in securing large castings. One is the tendency of the metal to give up dissolved gases, forming blow-holes, and the other is the tendency for the constituents—particularly such impurities as sulphur and phosphorus—to be unequally distributed throughout the mass. Nevertheless, large castings are obtained, weighing as much as 50 to 70 tons—the propeller brackets e.g. of the *Britannic* (Plate XXVI). It is usual to add a small quantity of aluminium to the metal before pouring into the mould, and this is said to produce a casting freer from cavities and of more uniform composition. Another method is to apply hydraulic pressure to the metal directly it is poured into the mould.

Not only is it necessary for structural purposes to have steel as uniform in quality as possible, but the development of the steam turbine has thrown a new and greater responsibility upon the steel manufacturer. The rotor of a turbine is a heavy mass of metal weighing several tons, spinning round at 1,000 revolutions per minute. As explained in the chapter on the steam-engine, enormous forces are brought into play if the centre of mass is not at the geometrical centre. For such work as this forged steel is often used and great expense is incurred in machining that would be unnecessary if cast steel could be relied upon.

The fact that steel can be both cast and forged has brought together two groups of operations which were formerly quite separate: the foundry and forge.

Forging is the process of hammering, pressing, bending, and jointing metals while they are in a hot, pasty condition. In that respect it differs

from wire drawing, spinning, and stamping in which the metal is worked in the cold, though a good deal of heat may be produced by friction. Metals which melt at a sharply defined temperature are incapable of being welded in the ordinary sense, though processes of jointing them will be described later; wrought iron and steel are the most important welding metals. So long as the surfaces are hot enough, and free from a coating of oxide, mere pressure will suffice to form a joint. In order to secure the necessary cleanliness a small quantity of borax or something similar, which melts and forms a protecting covering, is dusted over the surface. Any oxide which has been formed is dissolved in this film and is squeezed out by pressure. A welded joint is improved by subsequent hammering.

But welding is only one of the minor processes of forge work. It is mainly a manual process, and with the large masses of steel that are manipulated nowadays manual processes have little scope. The modern forge that has grown out of the mediæval smithy is a huge structure that hums with machinery and reverberates with the thud of steam-hammers. With the steam-hammer the metal may be subjected to the lightest tap or to a blow that shakes the very ground upon which the building stands. It is difficult to conceive of a tool with such a wide range of utility passing out of use, and probably no forge will ever be without one. But a century is a long time for any mechanical device to exist in its original form, and even today steel-makers are expressing a preference for the hydraulic press, first applied by Sir Joseph Whitworth in the middle of last century, and the rolling mill invented by Cort in 1783.

Perhaps the most interesting process allied to the use of the steam-hammer is drop-forging. The anvil contains the lower half of a die or mould, of the shape which the metal is required to assume. The upper half of the die is affixed to the under side of a heavy block of steel that can be moved up or down between guides. By means of a clutch this block can be drawn up to a height of from 2 to 10 ft. and allowed to fall. If, when it is raised, a piece of hot metal is placed in the lower die, the falling weight smashes it at one blow into the required form. In this way many parts of a modern motor-car are constructed. Where the change of form is only slight the metal need not be heated, a single blow in the cold being sufficient for the purpose.

As an example of modern forge practice we may consider the formation of a large, seamless steel tube, produced by the Darlington Forge Company. It is 9 ft. inside diameter, 7 ft. 8 in. long, and weighs 26 tons. The steel was first cast into a solid ingot, then a small circular hole was cut in the centre, and the mass of metal expanded in the hydraulic press to the required size for machining. The reader of an arithmetical turn of mind may be interested in calculating the thickness of the metal

from the dimensions given above and the fact that 1 cubic inch of steel weighs 0·26 lb.

Forging is at the best a crude process, and the machine shop has always to be requisitioned to finish off the handiwork of the smith. An allowance must always be made for the amount to be removed in the lathe or planing machine, and as these are, or were until recently, relatively slow, it was customary for the smith to work as closely as he could to final dimensions. The invention of high-speed tool steel, however, has made machining a cheaper process than accurate forging, and has considerably modified forge practice. It now costs less to run a lathe

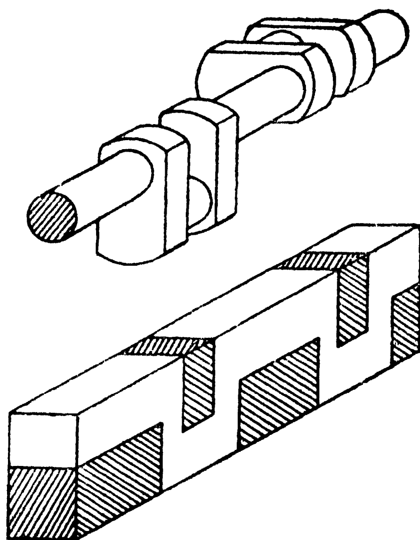


Figure 45. How a crankshaft is made

or planer than to maintain the furnace and steam-hammer. An interesting example is given in Harbord's *Metallurgy of Steel.* A 6-in. crankshaft with the cranks at right angles would formerly have taken a long time to forge, and would have left the smith with only a thin skin of metal for the machine hand to remove. Nowadays it would be cut out of a slab like Fig. 45, the shaded portions being removed by a band saw in the cold. The cranks are then in one plane. The shaft would be heated and twisted until the cranks were at right angles, and the portions of the shaft between roughly rounded by a light steam-hammer. The surplus metal would then be removed in a machine at the rate of 130 lb. per hour.

Of the other many interesting developments of the smith's art, space

will not permit description. The ignorance as to the composition of iron that made Bessemer's process a commercial failure for the first four years has been dispelled, and the metallurgist no longer works by rule of thumb. Not only the effect of composition, but also the effect of previous history, on the properties of steel is now known with a degree of accuracy that would have astonished the ironfounder of fifty years ago. The Engineering Standards Committee have laid down exact specifications of the material to be used for various structural purposes, and the fiery furnaces, obedient to the intellectual control of man, pour out 500 tons of iron or 50 tons of steel per day, with a composition that can be calculated beforehand to one part in a thousand. The new century has presented man with materials that raise engineering from a primitive art to an exact science; for he has learned to look beyond the mere naked-eye appearance and the approximate results of a crude test. Armed with the microscope, X-rays, and the electron-microscope, he penetrates the hidden molecular society of which the steel is composed, and assures himself of the presence of that arrangement which brings strength.

IX

THE ELECTRIC FURNACE

In 1892 Henri Moissan, of the Sorbonne, in Paris, commenced a series of investigations on the electric furnace, and thereby sowed the seed of industries which now utilize several million horse-power. He discovered a number of new substances, and laid the foundation of manufactures which have exercised a profound influence on economic development. Other substances of great industrial value, which were scarce because they resisted the high temperature of the blast-furnace, became available in quantity and in a high degree of purity. New fields were opened for industrial enterprise, a fresh impetus was given to water as a source of power, and great factories sprang up around Niagara, in the Alps, and on the steep hill-slopes of Norway and Sweden. The hum of machinery arose once more amongst the mountains.

Apart from the use of heat as a source of power, the value of a high temperature depends upon three facts. Firstly, most bodies melt, and can therefore be moulded and cast into any desired form; secondly, the fluid condition renders mixtures more intimate and facilitates chemical change; thirdly, many substances are resolved into their elements and many new compounds are formed.

When Moissan began his experiments probably the highest temperature employed in industrial operation was about 2,000° C. Consider what this means. Water melts at 0° C. and boils at 100° C. Tin melts at 235° C., lead at 330° C., and zinc at 420° C., all below red heat. Then among the more commonly occurring metals there is a gap until we reach those of the coinage—silver, gold, and copper, which melt at 945° C., 1,035° C., and 1,050° C. Higher up the ladder of temperature cast iron melts at 1,000° C., pure wrought iron at 1,600° C., and platinum at 1,770° C.

The temperature of a blast-furnace probably does not exceed 1,600° C. at the hottest point, and to get a higher temperature it is necessary to use gaseous mixtures in which the particles come into more intimate contact with one another. In the puddling process the iron became pasty

as the carbon was removed, while in the Siemens regenerative furnace, heated by gas, the metal remains perfectly liquid at the end of the operation. In the Bunsen flame, fed with the proper mixture of gas and air, a temperature of 1,870° C. is attainable; 2,000° C. is produced by a mixture of oxygen and hydrogen; and 2,400° C. by a mixture of oxygen and acetylene.

But in none of these cases can the actual temperature of the flame be communicated to the substance on which it plays. By an inexorable law of nature heat flows from a high temperature to a low—downhill and not uphill—and some of it is lost in the transfer. A large amount is carried away by the waste gases, some is lost by radiation, and some escapes by conduction and convection. All these losses can be reduced by enclosing the flame in a casing which offers considerable resistance to the passage of heat, and this is the main advantage of a furnace over an open fire or flame. The heat is produced by the energy with which substances enter into combination, and the temperature will rise as more and more heat is generated, until the amount lost in a given time is equal to that produced in the same interval.

Moreover, when the temperature reaches a certain point the very substances whose formation produces the heat begin to decompose; the combination is no longer possible, and the change which led to the evolution of heat is reversed. There is therefore a limit to the temperature obtainable in this way, which is independent of the losses by waste gases, radiation, conduction, and convection.

Now the conversion of electricity into heat is based upon a different principle. The passage of a current through a conductor is invariably attended by the production of heat, and a corresponding amount of electricity disappears. The greater the resistance which the conductor offers, the greater is the amount of heat produced. If, therefore, a copper wire, which is a good conductor, is replaced for a short distance by a wire of the same material but of smaller diameter, or by material of lower conductivity, a much greater amount of heat is produced there than at any other part of the length through which the electricity flows.

Again, the heating effect of a current is proportional to the square of its length. A current of 2 amperes produces 4 times the amount of heat that a current of 1 ampere will produce; a current of 3 amperes 9 times, a current of 4 amperes 16 times, and so on. If, therefore, a powerful current is conducted to a furnace by heavy copper cables and is then required to pass through loosely packed material of low conductivity and high resistance, this material may be raised to a white heat. Such an arrangement is called a resistance furnace because the heat is produced by the high resistance of the material with which the furnace is charged. On this principle furnaces were constructed by Sir William Siemens in 1879 and Cowles in 1886. The Siemens furnace is shown

in Fig. 46. It consisted of a carbon crucible which was attached to one wire (or lead) of the source of supply, and a carbon rod [1] dipping into the material which was connected with the other wire. In this way a pound of iron was melted in an hour, and many other experiments were made which showed that the discovery was of great value. Siemens

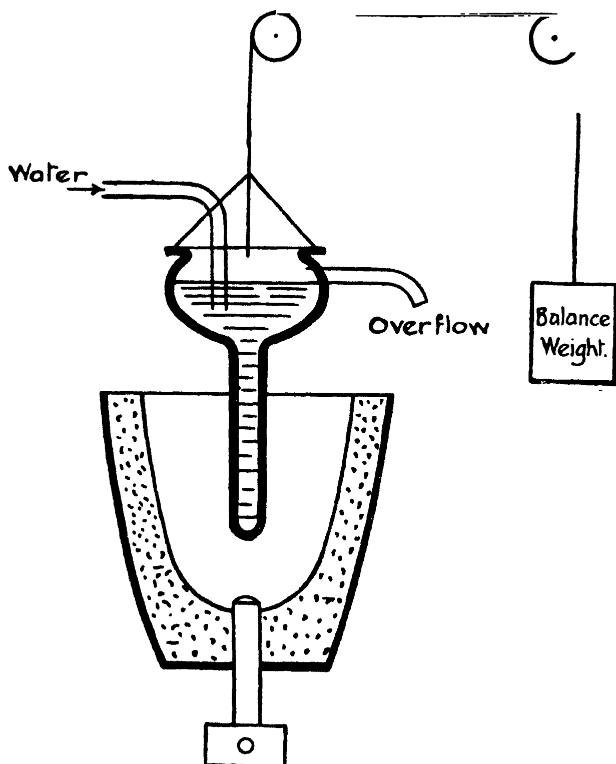


Figure 46. Diagram of the original electric furnace invented by Sir William Siemens

also constructed an arc furnace, which is shown in Fig. 47. Cowles' furnace was used on a commercial scale for preparing alloys of aluminium and copper.

The disadvantages of these furnaces for accurate laboratory experiments are the varying resistance due to the closeness or otherwise of the packing, and the alteration in composition during the process. Moissan therefore employed a different type, called an 'arc' furnace, of

[1] The diagram shows a water-cooled metal electrode which was sometimes used instead of a carbon rod.

which one form is shown in Fig 48. The current is led in by two carbon rods which meet just over the substance under experiment, and are then



Figure 47. Siemens' arc furnace

separated. The points in contact are raised to a white heat, and when they are separated the electricity bridges the gap so formed and produces the highest temperature which has hitherto been obtained.

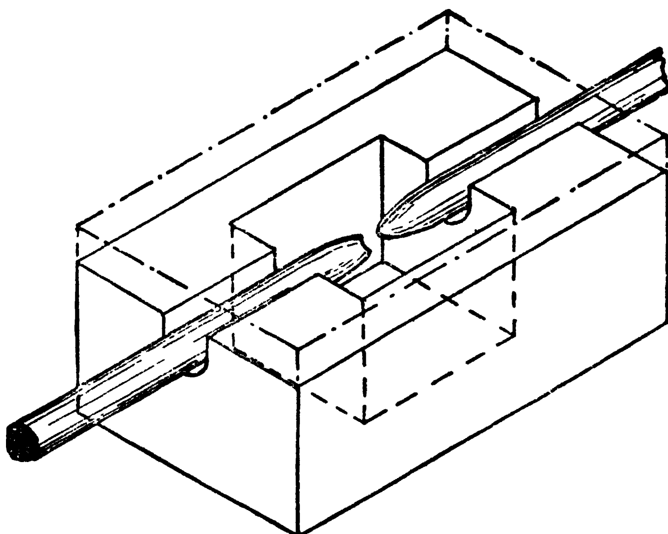


Figure 48. Moissan's electric furnace

Moissan's furnace body consisted of blocks of lime enclosing a cavity in which the substance to be heated was placed. The cavity was covered

with a block of lime to prevent loss of heat or access of air. The heat was thus concentrated in a small enclosed space, and the non-conducting property of the lime served to prevent loss. Thus in one experiment the cover was 3 cm. (1¼ in.) thick, and yet when the current had been switched on for ten minutes, and the under surface was melting, it could be lifted by hand. Magnesia will withstand a higher temperature than lime and has the advantage that it is the only oxide that is not reduced by carbon at the temperature of the furnace; but it conducts heat more readily. When it was necessary to use it, thin plates were employed as a lining alternately with plates of graphite. In some of the experiments on a larger scale the furnace consisted of blocks of limestone, which were speedily converted into lime. The absence of any materials other than lime or magnesia or carbon rendered it possible to prepare substances of a high degree of purity.

In the earlier experiments the electricity was supplied by a 4 h.p. gas-engine and dynamo, which gave about 40 amperes at 55 volts. Later a 45 h.p. steam-engine driving a dynamo giving 440 amperes at 80 volts was used. Finally, 100, 150, 300 h.p. was concentrated in the form of heat in the small enclosure containing the substance under examination. The temperature attained is impossible to measure accurately and difficult to estimate. But it certainly reached 3,500° C., and probably 4,000° C. would not be an exaggeration.

Under the influence of the enormous concentration of the higher powers employed the limestone gave off torrents of carbon dioxide, then the lime began to melt, and for experiments requiring the highest attainable temperature the lining of magnesia and graphite had to be used. The glowing crater could not be observed with the naked eye, and dark glasses had to be worn.

All the metals that melt below 1,000° C. or 1,200° C. boil in the temperature of Moissan's furnace. Thus in five minutes 103 grams of copper lost 26 grams, and flames of luminous copper vapour half a yard long streamed out of the holes through which passed the carbon rods. The fact that gold is volatile at temperatures near its melting-point has long been known, and special precautions have to be taken in assaying the precious metal to prevent loss by vaporization. In the electric furnace 107 grams of gold lost 52 grams in a very short time!

The advance which this discovery represented may be gauged from the fact that the hour required to melt one pound of iron in Siemens' furnace thirteen years before was now reduced to a few minutes. Even 4 lb. of the far more difficultly fusible chromium were melted in an hour, and on one occasion no less than 22 lb. of molten metal were obtained. Many other substances, such as manganese, tungsten, molybdenum, titanium, vanadium, and silicon, were chemical curiosities, and had only been obtained previously with great difficulty in small quantities. They

all have a profound influence on steel, and are essential constituents, with chromium and nickel, of most of the special steels which are now made in such quantities, and which have had such an important influence on modern manufacture.

Thus guns, projectiles, armour plate, tools, tyres, axles and other parts of machinery owe to a large extent their progress to the quantity and cheapness of substances which improve the quality of the steel used in their construction. Chromium confers toughness, tungsten and molybdenum hardness, titanium soundness, and vanadium strength to the material when added in appropriate amount. Manganese in quantity greater than 8 per cent gives exceptional hardness combined with ductility, and destroys the magnetic properties of the steel. Silicon in small percentages produces a suitable steel for springs. A new industry has thus been created to supply rich alloys of iron with chromium, tungsten, molybdenum, titanium, and vanadium, which are added to steel to render it more suitable for some specific purpose.

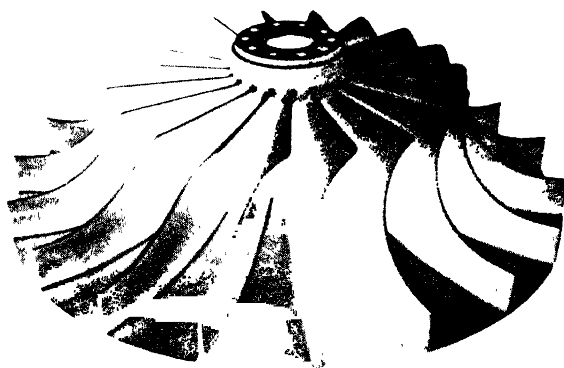
But to limit the world's debt to Moissan to the creation of but one industry would be to understate the case. His work forms the starting-point for a dozen. In the course of his unsuccessful attempts to make artificial diamonds, he repeated and extended Berthelot's experiments on varieties of carbon. After proving that there were only three forms of pure carbon—amorphous carbon, graphite, and the diamond—he showed that the first and the third are converted into graphite at the temperature of the electric furnace. Natural graphite is somewhat scarce; it occurs in inaccessible districts, and there has been an increasing demand for it in recent years. It is now made in quantity at Niagara merely by passing a powerful electric current through anthracite, and is one of numerous substances now manufactured by electric processes where cheap power is available. The pencil with which you write, the 'blacklead' used to polish the grate, the material that reduces the friction of the machinery in the neighbouring factory, the cores of the carbons in the arc lamps which illuminate the streets of the town in which you live, the graphite blocks which imprison the neutrons in an atomic pile, may all have had their origin in the dark recesses of an American mine. Torn from its hiding-place by giant power, packed in trucks and hauled up the shaft at 600 ft. a minute, it is whirled half-way across the continent to the foot of the Falls. There it is charged into a brick chamber, and subjected to the glowing energy of an electric furnace, which converts the hard black lumps into a fine, impalpable material, soft and greasy to the touch, and capable of innumerable uses for which it was originally unsuited.

The emery wheel originally used in grinding machines was made of a hard natural oxide of aluminium mixed with some binding material and compressed into discs. Rotating at a high speed, it was capable of

rubbing off rough edges of metal with the production of showers of sparks, quickly causing the metal to become red-hot. Since that time grinding has become one of the most accurate and useful workshop processes, capable of the delicacy required for scientific instruments, and the energy necessary for truing up an armour plate. But modern wheels are mostly made of a new substance, called carborundum, composed of carbon and silicon, and having the formula CSi. In 1893 Acheson of Niagara produced 6¾ tons, and nine years later 2,700 tons. His furnace was extremely simple. It was not a permanent structure, but was built up for each operation. A brick pit or box 15 ft. long, 7 ft. wide, and 7 ft. deep had fixed in each end sixty carbon rods each 3 in. in diameter and 2 ft. long, mounted in bronze sockets. The furnace was filled with about 10 tons of a mixture containing 34 per cent coke, 54 per cent sand, 10 per cent sawdust, and 2 per cent salt. The sawdust rendered the mass porous. Between the carbon poles was placed a core of finely broken coke along which the current passed. On dismantling the furnace the carborundum was found in a zone round the carbon core. Outside this zone was another substance, called siloxicon, having the composition C_2Si_2O. It is highly refractory and is used for furnace linings.

Probably the most important product of the electric furnace is calcium carbide, CaC_2. The value of this substance lies in the fact that on the addition of water it yields acetylene, C_2H_2, a gas of high calorific and illuminating value, the use of which for welding and cutting has been described in Chapter VII. A very common method of obtaining the gas is to use a holder similar in principle to the arrangement found in chemical laboratories for producing sulphuretted hydrogen. Most boys are probably familiar with Kipps' apparatus so frequently employed for this purpose. An acetylene generator consists of a gas-holder inverted over water, and a perforated box containing the carbide. As the latter is decomposed slowly by moist air, gas is being formed even when the apparatus is not in use. It is necessary therefore to limit their charge of carbide to the full capacity of the holder. Acetylene can also be obtained compressed in steel cylinders, but before this could be accomplished some difficulties had to be overcome. The formation of the gas is accompanied by absorption of heat, and it is therefore somewhat unstable. When it decomposes this heat is evolved. A chemical change that is accompanied by an evolution of heat is invariably more easily effected than one in which heat is absorbed. In the early attempts to compress acetylene in the same way as oxygen, hydrogen, and other cases are compressed, some explosions occurred. The heat engendered by the compression was so liable to cause an explosion that the method had to be abandoned. It was found, however, that the gas was very soluble in acetone, so the practice now followed is to compress it into a steel bottle partly filled with this liquid, which yields up its excess when the valve

XXVII*a*. Electric furnace pouring



(*High Duty Alloys*)

XXVII*b*. Forged aluminium alloy impeller for the de Havilland Ghost jet engine

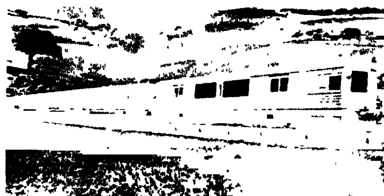




(*I.C.I.*)

xxviii*a*. Cold rolling aluminium

xxviii*b*. The main undercarriage of the Bristol 'Brabazon' made of aluminium alloy forgings



(*Ritchie Bros., Sydney*)



(*Eric Ross, F.R.I.B.A.*)

xxviii*c*. Silver City Comet diesel train, New South Wales Government Railways train, made of aluminium alloy

xxviii*d*. Aluminium doors on a giant hangar

is opened. Acetylene is used for lighting country houses, and in this case the low-pressure system first described is used. For welding and cutting metals either a low-pressure generator, or *acetylene-dissous*, as the compressed gas is called, is employed, but for large work of this kind the compressed gas is necessary.

Calcium carbide is produced by heating lime and carbon in an electric furnace, and as such furnaces have been in operation since 1885 it is curious that its value was not recognized before. A considerable quantity of it must have been formed incidentally and regarded as waste material. In fact, Vivian Lewis stated that the boys at the Cowles Aluminium Works were playing with it in 1887, at least five years before it was known to be of commercial importance. Since 1903 it has acquired a new interest. As explained in another chapter it absorbs nitrogen at a temperature of about 1,000° C. forming calcium cyanamide, a valuable manure sold under the name of 'nitrolim'. The nitrogen for this purpose is obtained by the liquefaction of air and subsequent distillation.

THE ELECTRICAL MANUFACTURE OF STEEL

In addition to the production of alloys of chromium, tungsten, molybdenum, and other metals with iron, to which reference has already

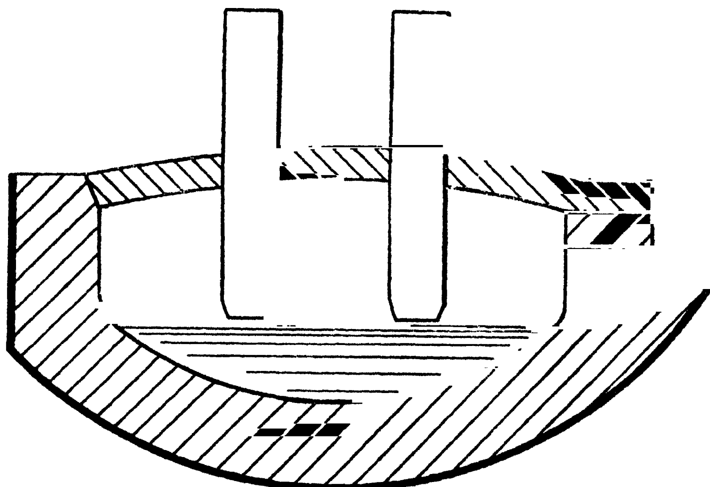


Figure 49. Héroult refining furnace for steel

been made, the electric furnace has also been developed for the manufacture and refining of steel. The Héroult furnace, shown diagrammatically in Fig. 49, has been established at Froges, in France. Another type,

using three-phase current, and therefore requiring three electrodes, is shown in Plate XXVII*a*, with the molten metal pouring from a vent near the bottom. It is really a refining furnace, and is based on the principle involved in the original furnace of William Siemens. The material—in this case molten steel—forms one electrode, and the other is a pair of large rectangular blocks of graphite, dipping into it. By raising the electrodes until they just fail to touch the surface of the metal a pair of arcs is obtained, but by lowering them into the liquid metal heat is produced by the resistance. The lower part of the container is curved and provided on the outside with teeth which engage with those of a straight rack, so that the furnace may be tipped for pouring. Several similar furnaces have been designed.

One disadvantage of this type, however, is the expense of renewing the carbon electrodes. A furnace which not only avoids this difficulty, but possesses the merit of constituting a very remarkable scientific achievement, is developed by the Swedish engineer, Kjellin, and others. The reader will probably be aware of the principle upon which an ordinary Rhumkorf or sparking coil works, but if not the following explanation will make the mode of operation of the furnace clear.

If two wire coils of any shape, but preferably round, are placed in the same plane or parallel with one another, then stopping, starting, or varying the strength of an electric current in one coil will produce currents of electricity in the other. An alternating current sent through one coil 'induces' an alternating current in the other. The total electrical energy which passes through a wire in a given time is equal to the strength (measured in amperes) multiplied by the pressure (measured in volts). In the two coils considered the quantity 'induced' is very nearly equal to the quantity inducing it, but the number of volts in each is proportional to the number of turns of wire, and the number of amperes is inversely proportional to the number of turns. That is to say, if the second coil has half as many turns as the first the pressure will be half and the number of amperes will be doubled. The heating effect of a current flowing through a conductor is proportional to the square of its strength, so that if the strength of current is doubled the heating effect is four times as great, and if the strength is trebled the heating effect is ninefold, and so on. It is therefore possible by means of a current of small strength and high voltage to produce a current of low voltage but very great strength. Moreover, if the second coil is composed of a substance which conducts electricity less readily than the first, the heating effect will be greater—varying directly as the resistance. Thus, if the first coil is of copper and the second coil of iron, the heat produced would be six times as great as if both coils were of copper.

In the Kjellin furnace, see Fig. 50, a coil of wire with a core of soft iron is fixed at the centre of a ring-shaped trough of refractory material con-

taining the constituents in the form of iron, scrap steel, etc., in the proportion necessary for the grade and class of steel required. When an alternating current is sent through the coil, very strong currents

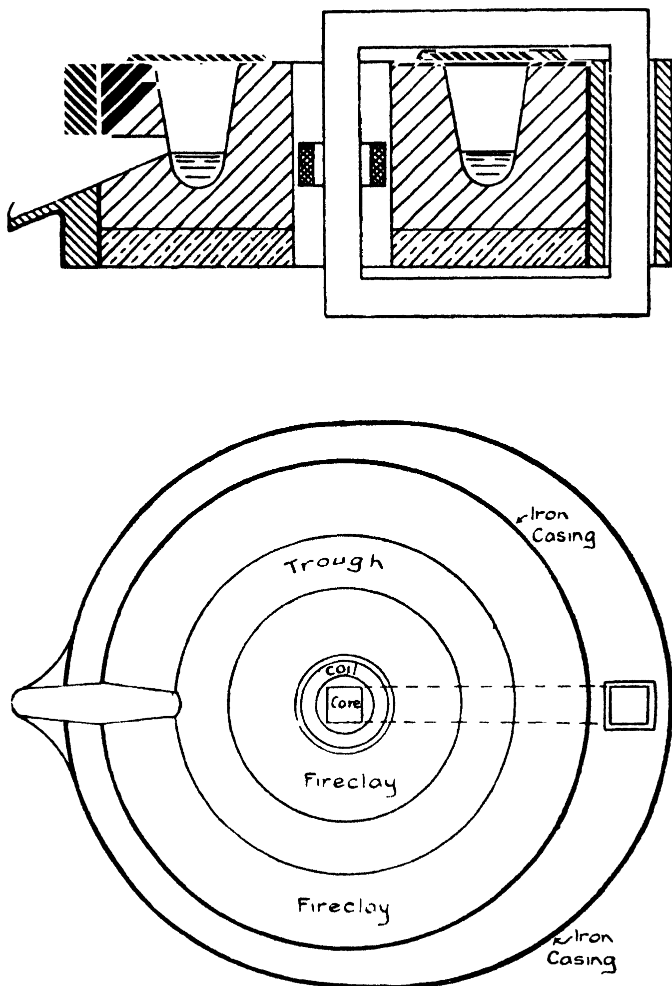


Figure 50. The Kjellin furnace

are induced in the ring of steel in the trough, and in a short time this is reduced to the molten condition.

The invention must be regarded as one of the greatest achievements of electrical science. Everyone has become familiar with the fact that

a crackling spark, or even an electrical tremor in a long wire, will flash signals across oceans and continents, but probably few realize that a coil which can be handled with impunity may be radiating energy that will reduce to the molten condition a mass of steel placed a foot or so away.

ALUMINIUM

In 1855, less than a century ago, the price of aluminium was £28 per lb. Even in 1885, the world production of aluminium was only 283 lb. Then, in 1886, P. Héroult in France and C. M. Hall in the United States independently discovered that the metal could be separated from oxygen by passing an electric current through molten cryolite in which aluminium oxide was dissolved. The price of aluminium fell from £3 per lb. in 1886 to 2*s.* 6*d.* per lb. in 1894. By 1951 the world production had risen to about 1,300,000 tons and the price had fallen to 10*d.* per lb.

Aluminium forms 8 per cent of the earth's crust, and is the most abundant metal, there being about twice as much aluminium as iron. Though it is an important constituent of nearly all rocks and clays, only one ore is of commercial importance. This is bauxite. It is a hydrated form of aluminium, produced by the weathering of rocks. It receives its name from Les Baux in France, where it was first found.

In 1949, the world production of bauxite was 7,749,000 tons. About half of this came from Surinam and British Guiana, in South America. Nearly all the cryolite used in the industry comes from Ivigtut in Greenland. The natural mineral resembles ice in appearance. The world production of aluminium in that year was 1,286,000 tons, of which the United States produced 547,000 and the United Kingdom 30,800 tons.

The crushed and dried ore is treated with caustic soda under pressure, forming sodium aluminate. The impurities, which mainly consist of oxides of iron, titanium and silicon, remain in the liquor. They are removed by filters, and collect in the form of 'red mud'. The filtered liquid passes to precipitation tanks. The introduction of seed crystals of pure crystalline aluminium hydroxide promotes the precipitation of the aluminium hydroxide.

When 70 per cent has been precipitated, the aluminium hydroxide is removed after the liquor has been filtered away. It is washed to remove caustic soda and then heated to 1,100° C. in a rotating tubular kiln. In this way, alumina in the form of a fine white crystalline powder is obtained, 99·4 per cent pure.

The alumina is dissolved in molten cryolite. This is a double fluoride of sodium and aluminium ($3NaF.AlF_3$). It is maintained at 950–

1,000° C., with additions of other substances which lower its melting-point. The cryolite is not itself used up in the electrolysis. The solution contains up to 5 per cent of alumina. A strong current is passed through

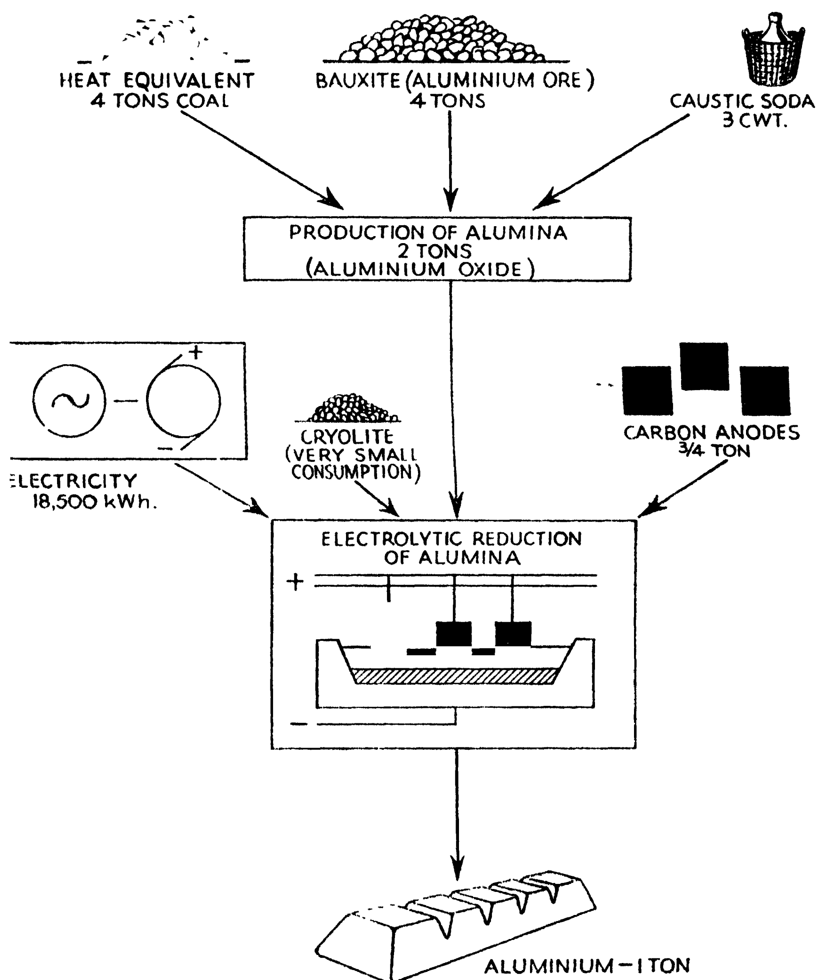


Figure 51. Principal materials and stages in the production of aluminium

it, in reduction cells. These consist of rectangular boxes made of mild steel, with a carbon lining which acts as the negative electrode, or cathode. The anodes are carbon rods, which are suspended in the liquid from overhead bars.

Aluminium from the reduction furnace is remelted (its melting-point is 660° C.) to remove dross, and is cast into ingots. It is 99·0–99·8 per cent pure, and a large amount of it is immediately used in the pure form.

When an alloy with different qualities is required, certain quantities of other metals may be added, such as magnesium, copper, or manganese.

The recovery and re-use of aluminium provides about one-quarter of the world's production.

Aluminium and its alloys are usually provided in wrought or cast form. Large quantities of aluminium powder are used in paint. Plate, sheet and strip are rolled from cast slabs weighing up to one ton. The slab is heated to 400° C., and reduced in thickness by about $\frac{1}{4}$ in. at each roll. It may be reduced to a thickness of about $\frac{1}{8}$ in. by a series of rolls, and then cooled, and cold-rolled. The rolls are highly polished to give a high finish to the sheet.

Aluminium foil is about 0·0003–0·006 in. in thickness. It has almost entirely superseded tin foil and silver foil for packing purposes. No less than 5,000 tons a year are used on the tops of milk bottles.

Aluminium is easily extruded. In this process a hot billet is put in a strong cylinder with a hard steel hole or die of the desired shape. The hot soft metal is forced through by a piston, which may be pushed by a force of up to 6,000 tons. Bars of very complicated shape for aircraft structures and other purposes can be produced in great quantity.

Aluminium tube is made by cold-drawing a hollow extruded blank over a steel mandrel.

The aluminium alloys whose properties can be modified by heat treatment are generally used for forging. Parts which work under high stresses, as in aircraft undercarriage gear, internal combustion engines, etc., are often made by forging. The original structure of the metal is broken down by the pressure, and a new grain flow or fibrous structure is developed in the directions along which the stresses will act. Hydraulic presses exerting up to 12,000 tons, and hammers weighing up to 20 tons, are used for these purposes.

When large quantities of an article are required, die-casting may be used. The metal is poured into iron or steel dies. A finer finish and faster production can be obtained by die-casting under pressure. The molten metal is pressed into a mould, which may be of a very complicated shape. The pressure helps to ensure that the article fits the mould very closely, and is of even consistency, producing highly accurate and sound articles.

Pure aluminium is normally covered with a thin film of oxide. This renders it immune to corrosion by the atmosphere, and even such substances as nitric acid, ammonia and sulphuretted hydrogen. Its excellence as a material for pans and kettles and other domestic utensils is due to this property. The natural oxide film can be thickened by electrolytic

or 'anodic' treatment, making a surface with remarkable resistance to chemical corrosion.

Aluminium alloys weigh only about one-third as much as steel and copper.

Pure aluminium is an excellent conductor of heat and electricity. Its electrical conductivity is about 60 per cent of that of copper, but, weight for weight, is about twice that of copper.

Alloys of aluminium-manganese and aluminium-magnesium are strengthened by cold working, e.g. being rolled when they are cold. Their tensile strength may be doubled in this way, an alloy containing 5 per cent of magnesium reaching a tensile strength of 20 tons per sq. in. after cold working (Plate XXVIII*a*).

Other aluminium alloys respond to heat treatment. Duralumin was the first of these. It contains additions of copper, manganese and magnesium. When heated to 500° C. and suddenly quenched in water, its properties change. This proceeds with time, or ageing. After four days, the tensile strength has doubled. The strongest heat-treatable alloys contain copper, magnesium and zinc. Their tensile strengths may reach 35 tons per sq. in.

Aluminium and its alloys can easily be riveted, brazed, soldered and welded. In spot-welding, a very heavy electric current is sent momentarily through the two pieces to be joined, at the point of joining. The current melts the metal, and produces a welt over a small area, or 'spot'.

In one of the newest methods, the pieces to be joined are melted by an electric arc at the place of joining. A flow of the inert gas argon is sent through one of the electrodes, surrounding the arc with an atmosphere of argon. No flux is necessary, and the speed of welding is greatly increased.

The applications of aluminium alloys are very wide in range. The structures, wings and fuselages, engines, undercarriages, etc., of modern aircraft are largely made of them. They are being used on a large scale in the most modern ships, trains, motor-cars, buildings, and in thousands of industrial and domestic applications (Plate XXVIII*b*).

The 53,330 ton flagship of the United States Lines, the S.S. *United States*, which has established the new speed record for crossing the Atlantic, contains more than 2,000 tons of aluminium in her structure.

The superstructure, which is 600 ft. long, is the largest aluminium structure which has ever been built on land or sea. The decks, interior bulkheads, windows and almost all the interior fittings are made of aluminium. The smoke-stacks, radar mast, handrails, and even the air-conditioned dog kennels, are made of aluminium alloys. The structures were assembled in large sections beside the hull and then hoisted into place. These were much lighter than structures of the same size in steel. Also 1,200,000 aluminium rivets were used. As in some other modern

ships all the lifeboats were made of aluminium. The internal fittings, such as air-conditioning piping, gratings, ladders, lockers, showers in staterooms, and most of the furniture are made of aluminium. Wood and other inflammable materials have been very largely replaced by aluminium, helping to make the ship more fireproof.

Fast light express trains are being made of aluminium alloys. The Australian 'Silver City Comet' is built of high-strength aluminium-copper-magnesium alloy in the structural sections. Clip angles and gusset plates are made of aluminium magnesium-silicon alloy, and sheet of aluminium-manganese alloy. The underframe, outer panelling, floor coverplates, seat pedestals, luggage racks, etc., are all made of the various alloys (Plate XXVIII*c*).

Aluminium alloys are used both for structure and decoration in building. An ornamental grille, made of aluminium-copper-magnesium-cadmium alloy, may be seen at the Sir John Cass Technical Institute in London.

The folding doors of the giant hangar for the Brabazon aircraft at Bristol are 65 ft. high and 1,045 ft. long. The total weight is 200 tons, and is carried by 96 sliding pilasters. Each of these is made of extruded aluminium (Plate XXVIII*d*).

The skeleton of the Dome of Discovery at the Festival of Britain Exhibition consisted of six lattice girders of extruded aluminium alloy, arranged as great circles in three directions. About 230 tons of aluminium were used in the dome.

The aluminium parts of sweet-wrapping machines are die-forged and bushed with hardened steel. They form and wrap from 500 to 850 sweets per minute.

Though aluminium is twice as abundant as iron, there seems to be little prospect that it will ever compete with iron in price. At present it is more than twenty times as expensive as iron. This is due to a fundamental reason. The aluminium atom clings to the oxygen atom with very much greater strength than iron to oxygen. Consequently, very much more energy is needed to separate them. As long as energy has an appreciable cost, the separation of aluminium from its ore will cost more than that of iron from its ore. If energy becomes very plentiful and cheap, as it may with the development of atomic energy, the cost of energy may become insignificant in comparison with other costs. In that case, aluminium might not be much more expensive than steel. About 18,500 kWh. of electricity are required to produce one ton of aluminium. Such enormous quantities can be produced conveniently only by hydroelectric power. Many big plants have been built for this purpose, and more are in construction.

The United Kingdom's home production of aluminium in 1952 was only about 30,000 tons, while the import of virgin aluminium was

230,000 tons, nearly all of it bought from Canada in dollars. Canada is interested in producing more aluminium, and the United Kingdom in finding alternative supplies which can be bought in sterling. These interests have led to the projection of great new aluminium plants.

The Aluminium Company of Canada, Ltd., is building a huge dam across the Nechako River in the mountains of British Columbia. It will be 300 ft. high and 1,500 ft. long. It will raise seven lakes along the river into a reservoir with a surface of 350 square miles. The flow of the waters will be reversed, and they will drain westward, instead of eastward as at present. The only escape for the water will be a tunnel ten miles long, which is being driven through a coastal mountain range. The lower end of the tunnel will be half a mile below the altitude of the lake. An enormous cavern is being burrowed out of the mountain, to contain the largest underground power station in the world. The initial generating capacity will be 450,000 h.p., rising ultimately to 2,000,000 h.p. The power will be taken on transmission lines over mountains 6,000 ft. high, where a new reduction works, and town, is being built at Kitimat. The ultimate production of the works is planned for 500,000 tons of aluminium per annum, equal to nearly half the world's present production, and twice Britain's consumption (234,102 tons in 1948).

A plan for a hydroelectric plant on the Volta River on the Gold Coast was published in 1952. It is proposed to build a dam and power station at Ajena about 70 miles from the mouth of the Volta River. The dam would create a reservoir with an area of 2,000 square miles. The generating station would produce 564,000 kW. The cost of the initial part of the scheme is estimated at £54,000,000. The construction of the dam and power plant would take from five to seven years.

An aluminium reduction plant would be built at Kpong, twelve miles from Ajena. This would have an initial capacity of 80,000 tons annually, and an ultimate capacity, achieved within twenty years, of 210,000 tons, that is, an output almost equal to the total British consumption of aluminium in 1952. The cost of the smelter and ancillary plant is estimated at £29,000,000. A new port, costing £11,000,000, would be built at Tema, 20 miles east of Accra. A railway would be built to transport the local bauxite from Yenahin to Kumasi, and from Kojoridua to Kpong. The cost of the total scheme is estimated at £144,000,000.

TITANIUM

Titanium is a metal of rapidly-increasing industrial importance. It looks and wears like stainless steel, but is less than two-thirds as heavy. It is chemically related to the metalloid silicon on the one side, and to the metal tin on the other. It does not occur free in nature, but it is the

fourth most plentiful of the metals of structural value, being fifty times as abundant as copper or tin. The known workable deposits of titanium, mostly in the form of the impure dioxide: rutile, or of the titanate: ilmenite, are vast and occur at many places in the world.

Titanium oxides produce a particularly dense white paint, and certain titanium compounds have remarkable electrical properties as insulators and dielectrics.

The production of titanium for structural and metallurgical purposes is a difficult technical problem on which much research is in progress. In Britain, the Imperial Chemical Industries Ltd. is working on the Kroll reduction process.

The melting-point of titanium is 200° C. higher than that of steel. The molten metal attacks all of the normal refractory bricks and materials used in furnaces, and the reduction and castings must be carried out in the complete absence of air.

The crude ore is first converted into titanium dioxide and then into titanium tetrachloride. The extraction of the metal requires the use of 1½ lb. of magnesium to every pound of titanium. The reaction is carried out in an atmosphere of argon, in order to exclude the air.

The magnesium is separated from the titanium by heating to about 1,000° C. in a high vacuum. The titanium remains as a spongy, coke-like mass, which is 99 per cent pure.

The spongy titanium is converted into ingots by melting in a special type of electric furnace. It melts at about 1,730° C., and is contained in water-cooled copper crucibles.

The difficulties of extraction have been overcome on the pilot scale, and techniques for casting ingots have been worked out. These have been successfully wrought into bars, rods, plates, sheets, strips, tubes, and wires, by rolling, extruding and drawing.

The density of titanium is about 4·5, between that of aluminium and steel. When suitably alloyed with aluminium, iron, chromium or manganese, it has a tensile strength of about 70 tons per sq. in., and 15 per cent elongation. It maintains an outstanding strength-to-weight ratio at all temperatures up to 500° C.

Besides having strengths as great as those of the high tensile alloy steels, the titanium alloys have great resistance to impact and fatigue. They are remarkably resistant to many forms of corrosion, and are particularly immune to attack by sea-water and marine atmospheres. The utilization of titanium scraps, however, presents an unusual practical problem. Metal turnings can usually be melted down and used again. This cannot be done with titanium scrap, and adds greatly to the cost of using the metal.

The reduction of titanium ores, and the subsequent melting processes, at present involve heavy capital investment and high operating

costs. But as these problems are resolved, immense new metallic resources will become available for industrial application. This is of vast importance in view of the rapid consumption of some of the rarer industrial metals, supplies of which cannot be expected to be forthcoming in their present amounts for a long period in the future.

SYNTHETIC MINERALS

The term 'stone age' has passed into ordinary language as a description of the primitive and backward. When man found out how to make copper and bronze metal tools, stone implements seemed to be finally consigned to a secondary position.

Though stone grinders and mill-stones long continued to be used for grinding corn into flour, cutting implements, weapons, and nearly all important tools, were made of metal.

The introduction of iron and steel gave a new importance to stones as sharpeners, but this was still only a secondary use.

Today the situation is changing. Stones are already superseding metals in some very important processes. For instance, carbide is superseding steel for the lathe cutting tools on which high-speed turning, and hence high-speed production, is becoming increasingly dependent.

Diamond has been used as a cutter since ancient times. Smoother surfaces can be turned with it than with any other cutter, and powdered diamond is still the most effective abrasive.

Quartz is used in thousands of tons, mainly for its piezoelectric property. If differing electric voltages are applied to the opposite faces of a suitably-cut quartz crystal, the quartz is distorted. By alternating the voltages it can be caused to vibrate. Conversely, a vibrating quartz crystal can produce extremely constant vibrations. These can be used to produce ultrasonic waves in water, as in the Asdic submarine detector, and to act as extremely accurate clocks, and wavelength controllers in radio.

The use of diamond, quartz, and other minerals has, however, been limited by their rarity and lack of uniformity of quality as found in nature. The prospect of the wide extension of their use has been opened by the development of the chemical synthesis of these minerals. During the last hundred years, great advances have been made in this line. Stones found in nature, such as quartz, sapphire and ruby, are now successfully manufactured by synthetic processes in the laboratory (Plate XXIX*a*). The possibility of synthesizing new stones not found in nature is in sight, and no doubt some of these will have unique properties, making entirely new processes possible.

It is agreed today that Hannay succeeded in synthesizing diamonds in

1880, but his process has not been repeated or developed. All diamonds used are still of natural origin.

Attempts to produce very hard substitutes for diamond abrasives led to the successful production of carborundum. This is made by heating a mixture of sand, coke, sawdust and salt in an electric furnace at about 2,000° C. Its manufacture was started on a large scale at the Niagara Falls, where large supplies of cheap electricity were first available. It has been followed by the manufacture of tungsten carbide, boron nitride, and other very hard materials, for cutting hardened steel.

Rubies and sapphires have been much used as very hard non-wearing bearings for watches and chronometers. As found in nature, both consist of the same material, corundum, a form of crystallized alumina. Ruby is crystallized alumina tinctured red through the presence of a little chromium. Sapphires consist of crystallized alumina tinctured blue.

Colourless corundum is now synthesized for the mass-production of bearings for watches and clocks by the method patented by Verneuil in 1902.

Finely powdered aluminium oxide is put in a funnel-shaped vessel, from which quantities of it can be tapped down at regular intervals. It drops into an oxy-hydrogen flame at 2,000° C. and melts. The droplets fall through the flame and settle, at the beginning, on a heated crystal of corundum. This acts as a seed, and incorporates succeeding droplets, so that they form the seed crystal. This, with its additions, is steadily lowered by a clockwork mechanism, which draws it out of the flame and cools it, thereby causing the additions to crystallize. Thus the seed crystal continually receives crystalline additions, and grows in size.

Synthetic mineral crystals can be built up in this way to lengths of several feet, but in practice the product is rarely more than a few inches long. The synthetic crystals are cut up and shaped into bearings by grinding with diamond powder.

During the Second World War, the Germans were very short of diamond dust, so they were unable to use corundum. Their chemists discovered, however, that spinel, which is made from a mixture of aluminium oxide and magnesia, and is normally much softer than corundum, could in fact be hardened if the proportions of aluminium oxide and magnesia were suitably chosen. If there is an excess of magnesia, it tends to separate out as little crystals. This greatly hardens in the spinel, in much the same way as the separation of crystals hardens steel and metallic alloys. This hardened spinel may be even harder than corundum. The Germans almost entirely replaced corundum by hardened spinel for bearings.

The Germans also worked out a process for synthesizing mica, an important material needed for electrical condensers. They succeeded in making mica crystals up to six inches in diameter. The synthetic mica

contained fluorine in place of the hydroxyl radicle found in natural mica. Tablets made of a compressed mixture of alumina, magnesia, silica and potassium silico-fluoride were melted at 1,450° C. By suitable control of cooling, the melt crystallized into mica. It was found that if a magnetic field was applied horizontally, the crystals grew with their planes perpendicular to the field.

Quartz is required in large quantities for the radio and telephone industries. Crystals of first-class quality are rather rare in nature. There has accordingly been a big and successful effort to synthesize quartz. The synthetic product is now more uniform than the natural, and is often preferred for this reason.

One method consists of holding a quartz seed crystal in a solution of sodium metasilicate and salt, together with silica glass, at a temperature of about 400° C. After several hours it is found that a new layer of quartz crystal has been formed on the seed crystal. The layer can be cut off, and used as a piezoelectric oscillator, and the seed crystal used over again.

In addition to these, many synthetic minerals are made for special purposes. Rochelle salt crystals, which have very strong piezoelectric properties, can be built up from water solutions of the salt.

A range of transparent materials for optical lenses and prisms, far surpassing those found in nature, has been produced in recent years by synthetic methods.

Fine crystals of sodium chloride and bromide have been made, and also of potassium chloride and bromide, lithium fluoride, and potassium iodide, silver chloride, and thallium salts. These have brought new regions of the non-visible spectrum within the range of exact investigation, and thus have led to a big increase in that knowledge of substances which is to be gained by examining the radiations which they emit in these non-visible regions.



REFRIGERATION

In days when the country was less thickly populated than it is now, and people lived farther apart, the land within a radius of a few miles from each homestead produced all that the family had to eat. The industrial revolution of the eighteenth century led to the rapid growth of towns, and each town was supplied with food mainly by farmers in the immediate vicinity. Before the advent of railways food was mostly eaten within twenty miles of the land which produced it. Moreover, it had to be eaten quickly. Many articles of food will keep fresh and sweet only for a limited time, and in hot weather this is very short indeed. Until the middle of last century the only way to keep meat sweet was by salting it. But too much salt food is not wholesome; mediæval armies, deprived of fresh food for some time, and the sailors who went on long voyages to remote parts of the earth, suffered terribly from scurvy. The value of ice for preserving food and in relieving fever was doubtless well known, for attached to many old mansions in England is an ice store. This consists of a thick-walled underground or semi-underground building generally located in a wood, and thickly thatched to keep out the warmth of the sun. Here were stored blocks of ice cut during winter frosts, to be used when the summer came round again. Then when the importance of preserving food became greater—when the population of the towns grew so that food had to be stored—ice was brought from Northern Europe in ships. And even today the south of France derives much of its ice from the glacier quarries of the Alps.

The British were formerly great beef-eaters. It is improbable that the great industries of the country could have been developed by a half-starved race of workmen. A growing anxiety made itself felt in the 'fifties, and about that time live cattle were first brought to England. It was estimated that the home production amounted to 910,000 tons per annum, or 72 lb. per head of the population. An importation of 44,000 tons of live cattle from America brought this up to 75 lb. per head. But America was not the only country which produced more than

its people could eat. Australia and New Zealand had rich pastures, and were raising mutton faster than they could eat it, and faster than they needed to produce all the wool they could sell. The trouble was—how to get it to the old country? Live cattle could be brought from South America—and as the population of the States grew, less and less beef was exported, and more and more tended to come from the rich grazing lands of the southern continent. Huge structures called 'lairages', where the cattle were slaughtered on arrival, were erected at Birkenhead and elsewhere, until the prevalence of foot-and-mouth disease in the Argentine led to an embargo on the importation of live cattle. But Australia and New Zealand were a long way off.

Many attempts were made at this date to preserve meat otherwise than by salting it, but most of them were doomed to failure. A more successful plan was to cook and can it, and today an enormous amount of tinned meat comes into this country. The home population, however, wanted uncooked fresh meat, and the colonists were able to supply it; so as it was known that meat kept better in frosty weather, the new and comparatively little-known process of freezing was tried, and the first cargo of frozen beef was brought from America in 1877. Three years later the first shipment of mutton from Australia reached these shores, and since then the trade has gone up by leaps and bounds. In 1910 we imported 13,000,000 carcases of lamb and mutton from Australia and New Zealand, and 250,000 tons of beef from the Argentine. In 1951, the home production of meat was 941,000 tons, and 515,000 tons were imported. Of the latter, 275,000 tons came from New Zealand, 87,000 from the Argentine, and 67,000 from Australia.

Nor does the story end there. Rabbits come from Australia, apples from Tasmania, fish, fruit, and dairy produce from Canada, and fruit from South Africa. How people would live without these vast supplies of food is an interesting problem. But the fact that they have not to make the attempt is due to the inventions and discoveries which have made cold storage possible.

THE ARTIFICIAL PRODUCTION OF COLD; THE MANUFACTURE OF ICE

As evaporation causes a liquid to cool, a machine which promotes evaporation can be adapted to produce cold. Substances usually employed include ammonia, sulphur dioxide, carbon dioxide, and organic vapours such as Freon and Arcton. These are based on di-chloro-difluoro-methane (CCl_2F_2). The first two, as most schoolboys are aware, possess extremely pungent smells and are highly injurious if breathed even in small quantities; the third, if breathed in quantity, would cause suffocation. Great care has therefore to be exercised in the construction of the apparatus to avoid the possibility of leakage. Ammonia gas can

be liquefied at ordinary temperatures by moderate pressures. Thus at 10° C. a pressure of about 100 lb. on the square inch is sufficient for the purpose, while at the ordinary pressure of the atmosphere the boiling-point of the liquid is − 33·5° C. At − 74° C. the liquid freezes to a white mass. Sulphur dioxide can be liquefied by passing it into a vessel immersed in a freezing mixture of ice and salt, when it condenses to a clear, mobile liquid which boils vigorously if the tube containing it is warmed by the hand. The boiling-point under ordinary atmospheric pressure is − 10° C. In both cases the boiling-point is, of course, much lower if the pressure is reduced, that is, if the vapour is pumped away as fast as it is formed. The drawbacks of ammonia and sulphur dioxide have been avoided by the introduction of Freon and other organic vapours, which are odourless and harmless.

Provided carbon dioxide is not hotter than 31° C. it can be liquefied by pressure. At that temperature a pressure of nearly 1,120 lb. per sq. in. is necessary. If the gas is no hotter than 13° C. a pressure of about 750 lb. per sq. in. will suffice. When a stream of the liquid (contained in a steel bottle) is allowed to escape through a canvas bag part of it evaporates, and this causes the remainder to freeze to a solid white mass which remains in the bag. This 'carbonic acid snow' does not evaporate very rapidly and can be used for maintaining very low temperatures. Mixed with ether it forms a pasty mass having a temperature of − 80° C., while if the vapours are pumped away the temperature falls to − 100° C.

Sulphur dioxide is largely used in creameries and bacon factories because the pressure is low, there is a good deal of condensation, and the pump lubricates itself and requires very little attention.

It is clear that carbon dioxide involves much lower temperatures and higher pressures than either ammonia or sulphur dioxide. For these gases the apparatus may be of cast iron, but for carbon dioxide every part which has to bear the pressure must be wrought out of forged steel.

It will be sufficient to describe two commercial methods that are used for the production of cold. In the first the ammonia gas is compressed into a spiral tube or worm by a pump, and the heat resulting from this compression is removed by circulating cold water through a vessel containing it, Fig. 52. The same pump then reduces the pressure in another worm into which the liquid flows and then evaporates. Air or brine circulating round the second worm is cooled and is then sent to the chamber or tanks, the cooling of which is required.

The pump is called the compressor. In the diagram it is shown as double-acting, taking in the ammonia through the inlet valves, and compressing it through the outlet valves at both ends. The gas passes at every stroke of the piston into the condensing worm, which is cooled by water. Thence it passes through a regulating valve, which reduces

the pressure somewhat, into the evaporator, where it vaporizes. The heat required for evaporation is abstracted from the air or brine which surrounds this worm. There is thus no loss of material, the gas or air and brine being kept continually circulating through the apparatus.

A plant of this kind has been used in the United States for an interesting purpose, which was originally suggested by Lord Kelvin in 1852. If, instead of water, air is used to cool the gas after compression the air becomes warmed. This warm air is then circulated through a building in winter, while air from the refrigerator is circulated in a similar way in summer.

Another method dispenses with the pump. It depends upon the fact that ammonia is very soluble in water, which dissolves, at the freezing-point, 1,160 times its volume of the gas. If this solution is heated the gas is given off, and if the apparatus is closed the pressure rises. The compressed gas is cooled in a worm or coil of piping as before and then

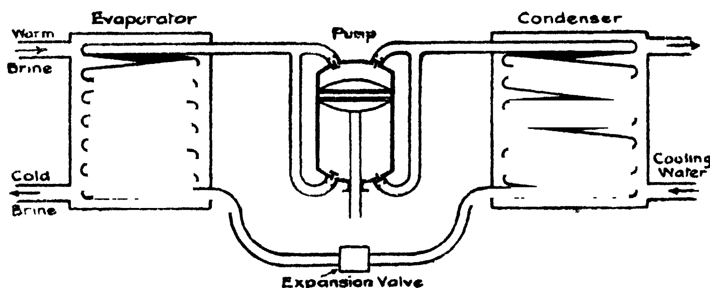


Figure 52. Diagram of refrigerating apparatus

allowed to evaporate in another coil. The evaporation is hastened by the gas being placed in communication with the weak liquor from which the gas has previously been expelled. Except for small details—chiefly for separating moisture from the gas in the first half of the process—the plan is very similar to the one already described. Instead of the backward and forward strokes of a pump, the ammonia solution is alternately heated by passing steam round the vessel containing it, and cooled by substituting water for steam. The method can only be used for ammonia; if sulphur dioxide or carbon dioxide is to be used, a pump is necessary.

If for any reason it is inconvenient to use air to convey the cold, a liquid which does not freeze at the temperature it is required to produce must be used, and for this purpose brine is employed. This brine is not always the solution of common salt to which the name is usually applied. Such a solution cannot be reduced in temperature below − 8° F., and

then only with 23·5 per cent of salt. With a higher percentage salt separates out before this reduction of temperature is reached and with a lower percentage ice separates out from the solution. A solution of calcium chloride containing 25 per cent of the salt is more generally suitable. This can be reduced to 18° F. below freezing-point without any separation of ice or salt occurring. In recent years a solution of magnesium chloride has found increasing favour. A 25 per cent solution remains liquid down to 22° F. below freezing-point and the solubility of the salt does not vary much with the temperature. In this respect it differs from calcium chloride and is similar to sodium chloride, but it can be used for lower temperatures than either.

The use of a refrigerating plant may now be described under the following heads:

(A) The manufacture of ice and the supply of refrigerating materials.
(B) The maintenance of cold stores on land and sea.
(C) Civil engineering and mining.
(D) The liquefaction of the permanent gases.

THE MANUFACTURE OF ICE

The large-scale production of ice has developed during the last fifty years. While the process consists essentially in freezing water in metal vessels by immersing them in brine at a low temperature, there are many details to which attention must be given if the ice is to find a sale at a remunerative price. If it is to come into contact with food or to be used for the table it must be prepared from water which is itself free from objectionable impurities. For although in the process of freezing water throws out dissolved substances, these are liable to be caught and encased in the interior of the block. Then, again, clear transparent blocks look better, keep better, and sell better than those which are opaque. Opacity is generally due to the enclosure of small bubbles of air, which can be avoided by using distilled water, or by gentle agitation up to the moment of freezing.

In one method of manufacture which is adopted, the water is contained in thin metal boxes or cans (Fig. 53), which are slung in rows on iron rods, and lowered into a tank through which brine at a temperature of 12° F. to 25° F. is circulating. The water in the cans is agitated by thin wooden paddles which move backwards and forwards automatically, and are removed before the water freezes, or by the ingenious method shown in Fig. 54. The vessel is made like a double-necked bottle, and one is used for each can. The lower ends dip well below the surface of the water, and the upper ends in each row are all connected with a pipe leading to the agitating pump. As the pump works, the water in the cans is alternately sucked into and forced out of the bottle, which is

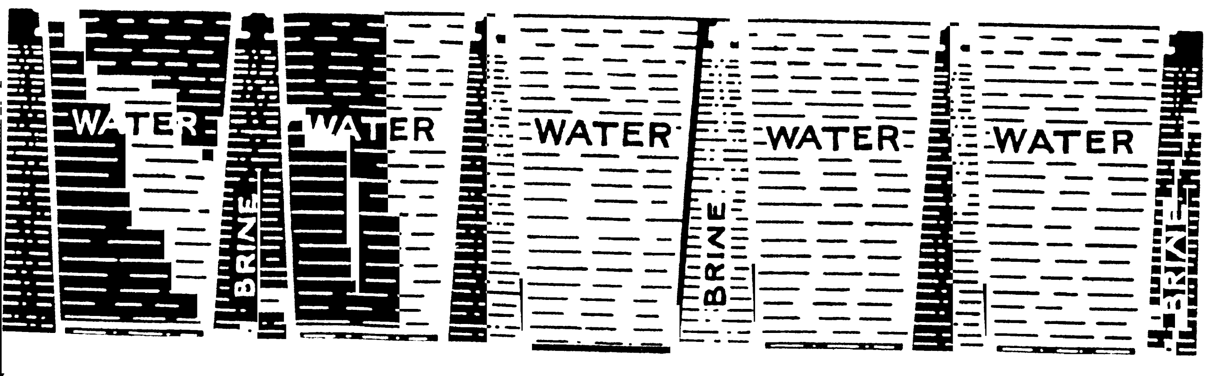


Figure 53. Diagram of the ice process

removed in time to prevent it being frozen in. The ice forms quickly at first, about an inch being produced in the first hour. After that the process is slower, 10 hours being required for 4 in., 36 hours for 8 in., and nearly 80 hours for 12 in. of ice. The cans are made in various sizes, but in the factory described each holds 1¼ cwt. There are twenty in a row, and forty-eight rows in all, so that the total capacity is 60 tons. As 48 hours are required to complete the process from start to finish, 30 tons of ice are produced per day.

Another method is illustrated in Fig. 55. There the water is contained in cells which are fixed to the false bottom of a tank through which cold brine can circulate. The whole of the cells together with the false

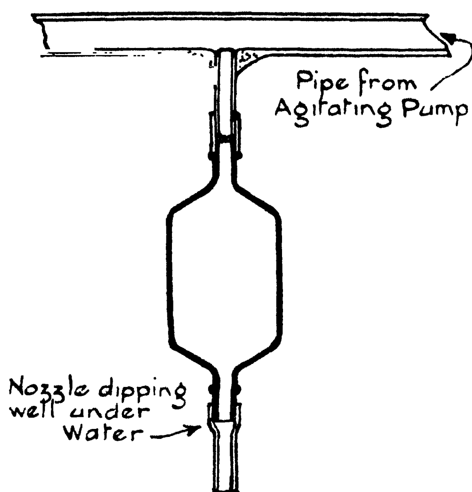


Figure 54. Agitating apparatus

bottom of the tank are filled with water, cold brine is circulated, and the agitating pump is set working. With each stroke of the pump water is alternately forced into and out of each cell through the hole in the bottom, and this keeps the water in constant motion until it becomes solid. Before this point is reached, a piece of rope with an eyelet is suspended in each cell, and is frozen into the ice block. The ice is loosened from the cells by switching off the cold brine and circulating warm. The blocks can then be lifted out by the rope eyelets.

A most interesting method has been adopted in America. A number of jets of water are allowed to escape into a large cylinder from which the air has been extracted. The nozzles rotate and move up and down along the axis so that the water is sprayed evenly over the inner surface. As the cylinder is immersed in cold brine the water freezes into a tube

Figure 55. Diagram of the all ice apparatus

about 6 ft. long and 4 ft. outside diameter, with walls a foot thick, which is sawn into blocks of saleable size. As this ice is formed in a vacuum there are no air bubbles, but the ice is opaque on account of its highly crystalline structure.

COLD STORES ON LAND AND SEA

When heat is required to pass from one fluid to another, a thin-walled metal plate is the best form of partition, and this has been used in the

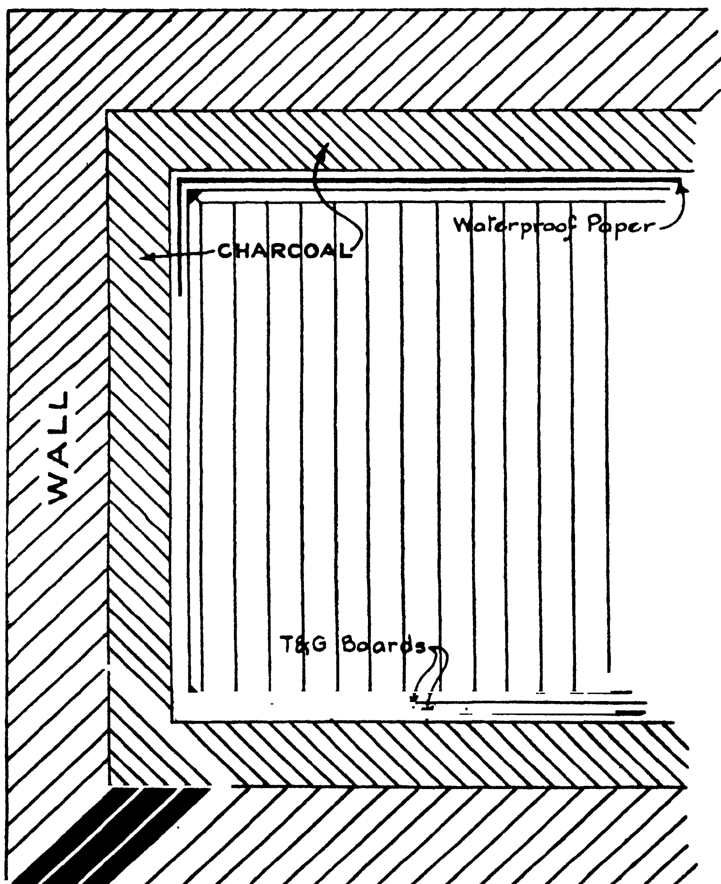


Figure 56. Horizontal section through cold stores

production of ice. But when a cold store is to be erected, in which perishable articles are to be kept at a low temperature, the walls must

be so constructed as to permit as little heat as possible to pass through from the outside. The building has, in fact, to be insulated. The walls are therefore made of considerable thickness (see Fig. 56) and are lined with 7 in. or more of flaked charcoal, silicate cotton, granulated cork, or some other material which offers a high resistance to the flow of heat. This insulating material is held up by an inner skin of boards. All steel girders, pillars, and other masses of metal are similarly covered with non-conducting material. These large rectangular buildings with five or six floors (see Fig. 57) are usually cooled by a current of air which passes over the brine pipes; but sometimes the pipes themselves enter the building with or without cold air. The circulation of air ensures better ventilation, but it is liable to be very dry, and this causes shrinkage

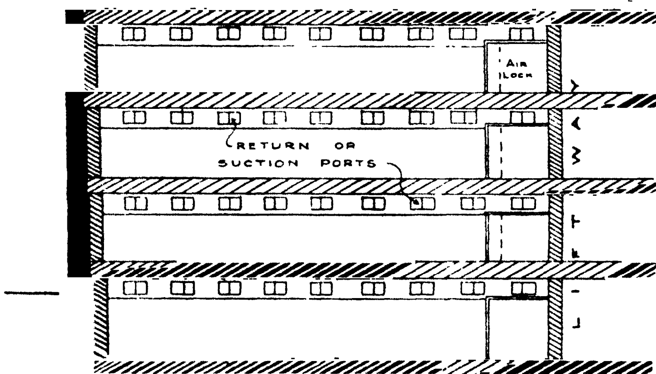


Figure 57. Vertical section through cold stores

of the food. The air is cooled by being blown through a network of brine pipes over which brine is trickling. In most cases a freezing temperature is not required. In the case of food the temperature need only be such that it will arrest the processes of decay; in the case of furs to prevent the hatching of moth's eggs; and in the case of wines to maintain that temperature at which the flavour develops most perfectly. The table on page 184 will convey some idea of the enormous variety of goods with which the cold storage manager has to deal.

But the table indicates something more than this. It conveys some idea of the great range of experiments which must have been undertaken in order to determine the most suitable limits of temperature for each article stored. Few outside the actual business of food supply and distribution can have any idea of the influence of cold storage on their

STORAGE TEMPERATURES

IN DEGREES FAHRENHEIT

<table>
<tr><th>10°</th><th>15°</th><th>20°</th><th>24°</th><th>26°</th><th>28°</th><th>30°</th><th>32°</th><th>34°</th><th>36°</th><th>38°</th><th>40°</th><th>45°</th><th>50°</th></tr>
<tr><td colspan="3">Frozen Mutton</td><td colspan="2" rowspan="2">Poultry Game for storing</td><td colspan="2" rowspan="2">Chilled Meat</td><td rowspan="2">Celery, Oysters</td><td colspan="3" rowspan="2">Vegetables, Fresh Fruit, Berries, Canned Goods, Furs (undressed), Syrup</td><td colspan="2" rowspan="2">Dates, Figs, Dried Fruits, Sugar, Wines, Flour</td><td rowspan="2">Clarets</td></tr>
<tr><td></td><td colspan="2">Ham and Butter (frozen)</td></tr>
<tr><td rowspan="2">Fish to freeze 0° to 5° Game to freeze 5°</td><td rowspan="2">Furs (long stor-age)</td><td rowspan="2">Frozen Meat (gene-ral), Rabbits</td><td colspan="4">Fresh Fish, Furs (dressed)</td><td colspan="2">Apples, Eggs, Cheese, Milk</td><td colspan="3">Bananas, Tomatoes, Peaches</td><td colspan="2">Oranges</td></tr>
<tr><td colspan="5">Woollen Goods, Carpets</td><td colspan="4">Cigars, Tobacco, Cider, Grapes, Potatoes, Lemons, Onions</td><td colspan="2" rowspan="2">Ale, Beer, Porter, Wines, etc. (in bottle)</td></tr>
<tr><td colspan="2">Frozen Eggs</td><td colspan="2">Margarine</td><td colspan="2">Hops</td><td colspan="3">Butter (short period), Lard, Pork, Ham</td><td colspan="3">Porter, Beer, Ale (in casks), Nuts</td></tr>
</table>

habits. One may see in a cold stores in the middle of November hundreds of Christmas birds plucked and frozen as hard as blocks of wood, waiting for the demand which experience has shown would come. Thousands of rabbits from Australia, packed in the same boxes in which they had travelled in the icy hold of a refrigerating steamer, are imported to supplement the supply of English rabbits, venison, capercailzies, pigeons, and other delicacies, ready at short notice to be exposed for sale in the shops, are kept in store. It has been said that cold storage has had something to do with keeping up the price of food, and certainly it prevents material being sold at any price to clear. The dealer in fresh meat, fish, and other perishable articles can keep a smaller stock in his shop, because he knows where to get more with very little delay.

In addition to these large stores, which are like furniture repositories in that they accept suitable goods at a rental until they are required by their owners, there are numerous specialized installations attached to particular industries, in which the manufacturing processes can be carried on most effectively at low temperatures. Thus refrigerating plants are often attached to dairies and butter and cheese factories, to bacon factories, to breweries, to dyeworks, and to many chemical works. It has been found that while the temperature of boiling water is sufficient to destroy all forms of animal and vegetable life, the roots and bulbs of many plants are not adversely affected by many degrees of frost. So long as they are exposed to a low temperature they remain dormant, but immediately they are removed to more genial conditions, they start into growth and come into flower in shorter time than under natural conditions. In this way plants can be retarded and flowers can be obtained over nearly the whole year. The trade in retarded plants has risen to enormous proportions. Every year thousands of bulbs of Japanese lilies are placed in cold store, while the number of crowns of lily of the valley so treated is measured in millions.

Turning now from provision on land to that on sea, every passenger vessel undertaking long journeys carries large quantities of fresh food in cold chambers. This not only relieves the tedium of a long voyage, but contributes materially to the health of the passengers and crew.

But cold storage at sea has a wider significance than that of comfort to travellers. The transport of the meat and many other foods imported for the populations of the United Kingdom and the industrial countries requires a huge capacity of refrigerated space. In 1952 the refrigerated space of the world's shipping had a capacity of 127 million cubic feet. The United Kingdom part of this amounted to 82 million cubic feet. Ninety-two per cent of the United Kingdom and 64 per cent of the world shipping refrigerated capacity was installed by Messrs. J. & E. Hall & Co., Ltd., of Dartford. The first source of our foreign meat supply was

the United States. The cattle were killed in Kansas City or Chicago and conveyed in refrigerator railway cars to Boston or New York for shipment. By 1901 the amount obtained in this way reached 160,000 tons. But the United States was growing rapidly, and from this time forward the trade was transferred gradually from North to South America.

In meat-carrying vessels the main body of the ship's hold is divided up into a number of chambers, along the roof and sides of which pass the pipes carrying the cold brine. While mutton, rabbits, and pork may be frozen hard without ill-effects, beef deteriorates considerably owing to the bursting of small blood-vessels. Practically all the beef, therefore, which has come to this country since 1899 has been submitted to a temperature of 28° F. to 30° F., and is known as *chilled* beef. Under these conditions its quality is unimpaired, and it will last three weeks in good condition. The fact that this is just long enough to enable the meat to come from South America and be consumed in this country is not without significance.

Extraordinary precautions are taken to secure cleanliness and to maintain a steady temperature. Each kind of meat carried must have a separate compartment, and while frozen carcases can be packed like ordinary cargo, chilled meat must be hung. The chambers are sealed and the seal must be unbroken at the end of the voyage. The temperature must be constant within a degree, and the difficulty of securing this in a vessel which crosses the equator can be imagined. The machinery is duplicated or even triplicated to provide for breakdown. The refrigeration machinery on a big refrigerator ship in 1952 cost about £120,000 exclusive of insulation. The latter cost a further £240,000, or £360,000 in all. In some cases self-registering thermometers have been used, but they are not always dependable. Another plan is for the engineer to take the temperature at stated times by lowering a thermometer down a tube leading from the deck into a hold; but the warm, moist sea air meeting the dry, cold air from below causes deposits of snow in the tube. Some years ago a very ingenious device was patented. An ordinary thermometer illuminated by an electric lamp is hung near the lower end of the tube, and the scale is reflected up so that the temperature can be read by an observer on deck. The human element is avoided by closing the upper end with a camera. At stated periods the *temperature* and the *time* at which the observation is made are photographed, and the film, when developed, is a faithful record of the conditions during the voyage.

Another industry which would be quite impossible on a modern commercial scale, without the processes which have been described, is sea fishing. In 1952 779 first-class trawlers of all types were registered in England and Wales, and all of these were equipped with refrigerating

apparatus. A voyage extends from two to four or five weeks. If you buy a *fresh* plaice from the fishmonger's it is not likely to have been caught less than a week ago, and it might be a month old.

CIVIL ENGINEERING AND MINING

The engineer has frequently to excavate in boggy ground, or in ground so wet and soft that the sides fall in before he can complete his task. He overcomes the difficulty by sinking brine pipes in the soil and freezing it solid, so that he can complete his excavations, lay his foundations, and build his walls. Once he has reached solid ground he can fill up the cavity with masonry and defy the bog or quicksands which formerly barred his way.

Again, the miner desires sometimes to reach coal or other minerals which lie beneath a bed of water-bearing strata. When he attempts to sink the shaft the water rushes in faster than it can be pumped out. In these circumstances a ring of vertical brine pipes is buried round the spot where the shaft is to be sunk, and the ground frozen solid in the form of a cylinder which holds back the water. As the sinking is carried on, the sides are bricked or 'tubbed' with an iron casing. The completion of the ice-wall takes from four to ten months, and it has to be maintained solid for from six to fifteen months to allow of the shaft being completed. Magnesium chloride is used in preference to calcium chloride or common salt because it can be relied on to a greater extent not to form any deposit in the pipes, which cannot be taken up for inspection and cleaning when once the process has been started.

HEAT PUMPS

A refrigerator takes heat away from where it is not wanted, and puts it in another place. Evidently, a refrigerator could be used as a heating appliance, if the heat delivered by it could be utilized conveniently.

Kelvin pointed out in 1852 that a heat-engine run in reverse could act either as a refrigerator or as a heating appliance. His theory of the refrigerator as a reversed heat-engine has been widely utilized in the practical development of refrigeration, but its application in heating appliances has only been quite recent. A reversed heat-engine for heating purposes is called a heat pump. The first installed in England was in Mr. T. G. N. Haldane's private house in 1930.

In ordinary refrigeration installations, say, for keeping meat, brine circulates in pipes through the cold room, and conveys heat from it to a working substance, such as ammonia, in the refrigerator. The cycle of the refrigerator concentrates the heat in the ammonia, raising its temperature. The ammonia is then run through a condenser, which

abstracts from it the concentrated heat. The brine must be at a temperature lower than the cold room and at a higher temperature than the ammonia delivered to the machine. If the cold room is at 30° F. then the temperature of the brine may be 20° F., and that of the ammonia may be 10° F.

The cycle of the engine will concentrate the heat in the ammonia, so that the latter's temperature will be raised to about 90° F. The ammonia will then be run through a condenser cooled by water at, say, 60° F. Thus, by the whole operation, heat from the cold room is ultimately

Figure 58. Diagram of a heat pump

carried away by the cooling water of the condenser, whose temperature is perhaps 30° F. higher than that of the cold room.

A simple form of heat pump may be illustrated by the installation built by Messrs. Escher Wyss of Zurich for a Swiss market garden.

The heat is obtained from water in the ground, drawn from a depth of 23 ft. The temperature of the water ranges, according to the season of the year, from 50° F. to 54° F. This water is pumped through the engine of the heat pump, which causes a transference of some of the heat in the water into the working substance, ammonia, of the engine. The temperature of the ammonia rises to about 203° F. and that of the water falls by about 7° F., after which the water runs to waste. The medium receiving heat from the working substance is the water which runs through the pipes in the greenhouse. This water is circulated through the pipes by the hot-water pump. It leaves the greenhouse pipes with a temperature of 104° F. and then passes through the condenser,

where it receives heat from the ammonia, which raises the temperature to 122° F. The water at 122° F. is now sent back through the greenhouse pipes. The data for the installation are given in Table I:

TABLE I.—HEAT-PUMP INSTALLATION

	Ground-water Temperatures.	
Evaporator	Inlet 50° F.	Outlet 43° F.
	Hot-water Temperatures.	
Condenser	Inlet 104° F.	Outlet 122° F.
	Ammonia Temperatures.	
Evaporator	Inlet 40° F.	Outlet > 45° F.
Compressor	„ > 45° F.	„ ≯ 203° F.
Condenser	„ ≯ 203° F.	„ ≯ 123° F.
	Ammonia Pressures.	
Evaporator	73·3 lb. per sq. in., abs., giving a saturation temperature of 40° F.	
Condenser	299·7 lb. per sq. in., abs., giving a saturation temperature of 123° F.	

The consumption of ground water is at the rate of 110 gallons per minute. This is pumped by a pump using 1·5 kW. The compressor is driven by a 35 kW. motor. The hot-water pump is driven by a small electric motor. The installation has replaced an electrically heated hot-water system together with three coal-fired boilers. The heat pump has a complete automatic control, through thermostats in the supply and return greenhouse pipes.

Before the installation of the heat pump, the heating of the greenhouse consumed 196,240 kWh. of electrical power, and an unspecified quantity of coal. When the heat pump was installed, the consumption of electricity went down to 65,000 kWh. and no coal was used. This represented a saving of all the coal formerly used, and a saving of £563 per annum on electricity (at 1*d.* per unit). Against this must be placed the interest on capital, and possibly on maintenance.

The Norwich Electricity Department has heated its large stores and workshop building with a heat pump. This building contains 500,000 cubic feet, and much window area. It is built beside the river Wensum, from whence the low-temperature heat is derived. The hot water for the heating radiators in the rooms is delivered to them at 120° F. The previous costs of heating by coal-fire had been carefully kept, and could be compared exactly with the performance of the heat pump. The figures are given in Table II on page 190.

Such an installation effects a financial saving. It is cleaner, and eliminates coal and ashes, and no stoker is needed. Coal is consumed with high efficiency at the central power station supplying the electricity,

TABLE II.—COMPARATIVE ANNUAL COSTS OF HEATING A LARGE BUILDING

Seasonal total heat supplied: 20,000 therms. Coal of heating value 12,000 B.Th.U. per lb. at 65*s*. per ton. Average combustion efficiency, 55 per cent. Cost of electricity: (*a*) loads on peak, 4*l*. per kVA plus 0·6*d* per kW-hour; (*b*) loads off peak, 0·6. per kW-hour. Average performance energy ratio, 4 : 1.

	Coal-Fired Boilers	*Heat Pump* Alone	*Heat Pump* With Thermal Storage
Capital cost, £	1,500	4,000	4,500
Annual capital charges, £	225 (15 per cent).	280 (7 per cent)	315 (7 per cent)
Cost of coal or electricity, £	440	601	367
Attendance, £	230 (including coal and ash handling)	--	—
Repairs and maintenance, £	150	50	50
Replenishing working substance, £	--	25	25
Total annual cost, £	1,045	956	765
Cost per therm	12·5*d*.	11·5*d*.	9·1*d*.

with low atmospheric pollution and production of smoke. It leads, too, to a reduction in the employment of low-grade labour. Finally, the total consumption of coal is reduced. Calculation shows that it goes down from 16·6 lb. per therm for the old installation, to 9·1 lb. per therm at the power station.

Heat pumps have been greatly developed in Switzerland, which has no coal, and whose coal supplies were interrupted during the world wars. They have utilized them for such purposes as heating swimming baths, and supplying large quantities of warm water for rayon factories. In the United States they have been developed especially for space-heating and air-conditioning. Where a source of low-temperature heat is available, as in ground water, rivers and the sea, all new large buildings, such as hotels and blocks of flats, in the vicinity should secure their heating by hot water at not more than 120° F., derived from the source by a heat pump.

In Britain, where many cities and towns are beside the sea and rivers, and the need for economy in coal is pressing, there are interesting prospects for the development of heating by heat pump.

LIQUID AIR

In none of the cases so far considered has the temperature been very low—certainly not lower than the natural cold of the Arctic and Antarctic regions. Far lower temperatures, however, can be obtained, and the practical results have been of first-rate industrial importance. From what was said in the earlier part of this chapter it will be obvious that the simplest and most effective method of producing cold is by the rapid evaporation of a liquid. The colder this liquid is and the more rapidly it evaporates the lower will be the temperature produced. Now the only substances which evaporate rapidly at low temperatures are those which at ordinary temperatures exist in the gaseous condition. Consequently, the problems to be studied are associated with those which occur in the liquefaction of gases.

In the first quarter of the last century Faraday liquefied chlorine by a very simple method. This gas was led into water contained in a vessel immersed in a freezing mixture. It formed a crystalline compound with the water. The crystals were placed at one end of a bent tube and the other end was sealed up. On warming the end containing the crystals the chlorine gas was evolved and condensed to a yellow, oily liquid at the other end. Using the cold produced by a mixture of ice and salt, he succeeded in liquefying sulphur dioxide, ammonia, and other gases.

Returning to the subject again in 1845, and using a mixture of solid carbon dioxide and ether, he liquefied sulphuretted hydrogen, nitrous oxide, and hydriodic and hydrochloric acids. The high pressures used involved no little danger. Faraday himself had some narrow escapes, but there seemed to be a fascination about the experiments, which attracted many scientific men. Caignard de la Tour and Colladon worked at the problem, and Thilorier had an assistant killed by the bursting of a cast-iron vessel containing liquid carbon dioxide which had been prepared for a lecture in Paris. The great problem was to liquefy the so-called permanent gases, oxygen, hydrogen, and nitrogen, which had so far resisted all attempts, though Natterer, for example, employed a pressure of nearly 60,000 lb. per sq. in. The most important step was taken by Andrews in 1868. He showed that in the case of carbon dioxide no amount of pressure would cause it to liquefy unless the temperature were below 31° C. This temperature is called the critical temperature, and the pressure required to liquefy the gas at that temperature is called the critical pressure. All failures to liquefy the permanent gases had occurred because the temperature had not been sufficiently low.

The first actual liquefaction of oxygen was accomplished independently and nearly simultaneously by Pictet and Cailletet. Both subjected the gas to enormous pressure and then allowed it to expand. Pictet merely opened a cock and permitted the gas to escape. This expansion

caused intense cooling, and a stream of liquid was obtained. It could not, however, be kept. Cailletet compressed the gas in a glass tube and then suddenly increased the volume by rapidly unscrewing a plunger. A mist, and then a meniscus separating gas and liquid, formed in the tube.

Further progress was made by Wroblewski and Olszewski working together, and subsequently by the latter alone. To high pressures they added intense cooling, by surrounding the vessel containing the gas by another liquefied gas which was kept boiling by a pump. In this way oxygen and nitrogen were liquefied and some of the properties of the liquids were determined. Soon afterwards Linde in Germany, Dewar

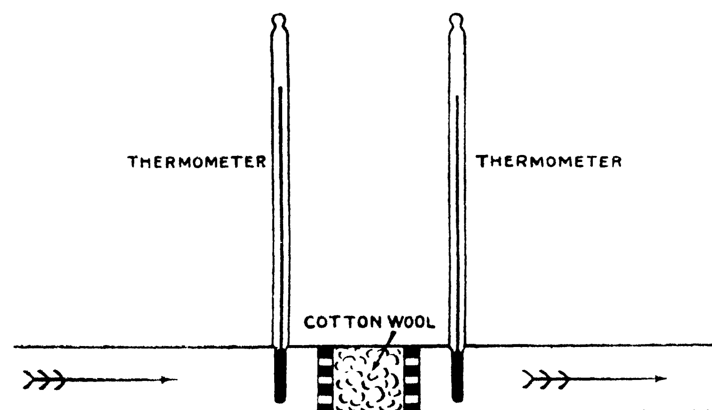


Figure 59. Kelvin's porous plug experiment

and Hampson in England, and Tripler in America succeeded in obtaining liquid air in quantities, and the problem which had baffled scientific workers for a century was solved.

In order to understand how this result has been achieved it is necessary to recall an experiment by Kelvin and Joule. If a gas expands without performing work, no appreciable cooling takes place. The cooling is a measure of the external work performed. For if there is an attractive force between the particles internal work must be done, and an equivalent amount of heat must be absorbed. Kelvin and Joule passed the gas through a porous plug in a tube fitted with delicate thermometers as in Fig. 59. The gas passed in the direction shown by the arrows. The slow diffusion of the gas involved no external work, and any difference between the readings of the two thermometers would be due to internal work. All gases except hydrogen showed a lower temperature (about $-25°$ C.), indicating that there was attraction between the molecules which had to be overcome during expansion.

Hydrogen gave an increase of temperature, and this could only be explained on the assumption that the molecules of hydrogen repelled one another. At a lower temperature it has since been found that hydrogen behaves in the same way as other gases.

The important and far-reaching principle just described enabled Linde, in 1895, to liquefy air by means of the apparatus shown in Fig. 60. Highly compressed air is passed through the inner of two concentric tubes, whence it issues from a fine orifice. This orifice serves the same purpose as the porous plug in Kelvin and Joule's experiment, and the issuing gas is cooled. The air passes back through the outer tube, thus lowering still further the temperature of the air before it leaves the orifice. As the air leaves the inner tube, therefore, it is continuously lowered in temperature until at last liquid air drips from the end of the inner tube into the vessel below.

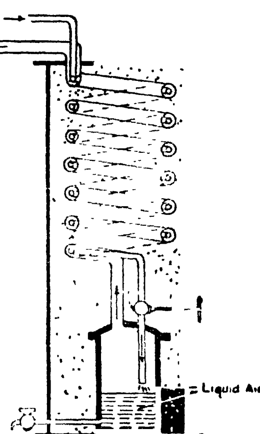


Figure 60. Linde's apparatus for liquefying air

That this liquid is air is hardly conceivable; the air that passes freely in and out of our lungs; the air that rustles through equatorial forests and moans through northern pines; the air that devastates the southern states of America and hurls giant steel ships on the rock-bound coast; and yet lying here tamed and with all the fire taken out of it. Now and then a turbulent bubble breaks from bondage, or an angry tremor ripples across its surface. Still, so long as it is kept in an open vessel it will pass away quietly into gas; but if an attempt is made to confine it in closed vessels it will burst its bonds and scatter its prison in a thousand fragments.

Liquid air boils at $-181°$ C. It is clear and colourless. A test-tube full of mercury plunged into the liquid is frozen into a solid rod which can be hammered into various shapes like wrought iron. Inelastic bodies become elastic, and indiarubber becomes so brittle that it can be broken with a blow of a hammer. A small quantity of the liquid poured into the boiler of a model steam-engine evaporates rapidly and causes the fly-wheel to spin round as though under a high pressure of steam, while the boiler becomes crusted with ice from the moisture in the atmosphere. At this temperature the electrical resistance of metals decreases to such an extent as to suggest that at a still lower temperature it would become a vanishing quantity. A soap bubble blown on the end of a thistle funnel and held in the vapour over the liquid becomes frozen, and when

struck upon a hard substance such as a table-top it is shivered into invisible particles.

In the course of his researches Dewar devised a flask, Fig. 61, which enables liquids to be retained for a considerable time at a low temperature. The Dewar flask has double walls, the space between which is exhausted of air. The object is of course to prevent the heat entering the flask through the walls, and if the air were left in, warmth would be conveyed to the inner vessel by conduction, and by convection currents, as well as by direct radiation. The first two processes are prevented by pumping out the air, and the effect of the latter is largely reduced by silvering the inner walls. Dewar found that if a small quantity of

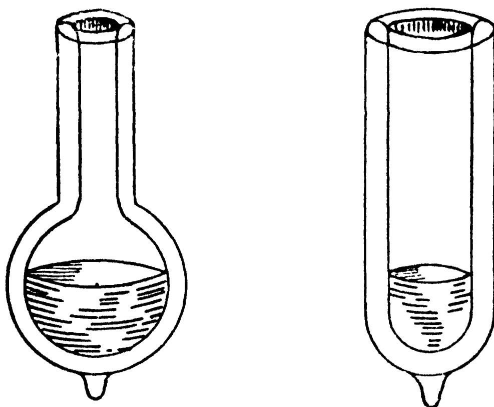


Figure 61. Two forms of Dewar flask

mercury was introduced into the space, its vapour condensed in a brilliant mirror which acted in a similar way.

Any arrangement which will prevent heat passing in one way will be effective in preventing its flow in the opposite direction, so that a body can be kept hot just as well as one can be kept cold. The well-known Thermos-flask is, in fact, simply a Dewar flask enclosed in a metal and leather case, and provided with a cover.

The liquefaction of air has had many important industrial applications. Oxygen gas has for many years been a regular article of commerce. It is required for blowpipes for brazing and welding, for scientific investigation, and for use in hospitals. The modern process was devised by Linde in 1895. It depends upon the fact that nitrogen boils at a lower temperature than oxygen, so that when air is liquefied and allowed to boil, the nitrogen passes off more rapidly than the oxygen. The apparatus is shown in Fig. 62. A continuous stream of liquid air flows into the vessel and the constituent gases are separated. The oxygen is

obtained practically pure, but the escaping nitrogen contains over 7 per cent of oxygen. By a process patented by Claude in 1903 this nitrogen is freed from all but a trace of oxygen, and then passed over calcium

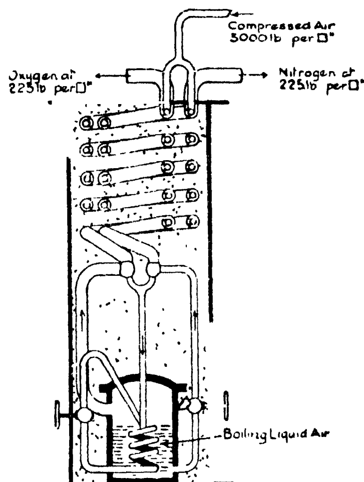


Figure 62. Apparatus for separating nitrogen from liquid air

carbide heated to a temperature of 1,000° to 1,100° C. so as to form calcium cyanamide. The importance of this substance as a fertilizer will be discussed in Chapter XI.

TOWARDS ABSOLUTE ZERO

The atoms of matter are in a perpetual state of random motion, which exhibits itself as heat. It is possible to conceive that all random atomic motions might cease. In that case, absolute cold, which would manifest itself as absolute zero of temperature, would be produced.

It is possible to calculate that the absolute zero is near to − 273·16° C. Great efforts have been made to approach it, but while it is relatively easy to move up the temperature scale, it is more difficult to move down, and it becomes progressively more difficult the lower the temperature.

If you strike an ordinary match, it bursts into flame, and in a moment its temperature rises about 2,000° C. But to go down from room temperatures to − 269° C. (the boiling-point of liquid helium), which is a fall of less than 300° C., bulky and powerful machinery working for a considerable time is necessary.

Roughly speaking, the difference is due to the fact that it is easier to put things into disorder than to put them into order. Raising the temperature increases the disorder, while to approach absolute zero it

is necessary to get all the atoms at rest in perfect order. In fact, each step in the ordering of the disorder becomes more and more difficult, so while it is possible to approach absolute zero very closely, it is impossible ever to get there. Suppose that you start with a gas at a temperature of 300° above absolute zero. Then it is as difficult to reduce the temperature from 150° to 75° as it is from 300° to 150°. It is as difficult to reduce from $\frac{1}{500}°$ to $\frac{1}{1000}°$ as from $\frac{1}{50}°$ to $\frac{1}{100}°$ above absolute zero.

The method which succeeded in cooling the gases so far that all of them became liquefied depended on making them do external work. The intensity of the random heat-motions was reduced by allowing the gases to do work through expansion.

The systematic liquefaction of gases was not completed until 1908, when Kamerlingh Onnes liquefied helium at 4·2° above absolute zero. He accomplished this only after ten years of theoretical investigation and then the construction of most imposing cooling machinery.

He compressed the helium gas, and then cooled it with liquid nitrogen, and then further with a bath of liquid hydrogen.

This was the culmination of a hundred years of work by many scientists on the production of cooling by expansion. As there were no more gases to liquefy, with different properties, there was no hope of much further advance by this method. Keesom took it to its limit when he reached 0·7° above absolute zero by attaching a series of huge mercury diffusion pumps to a flask of liquid helium no bigger than a thimble. By this means, the cooling by expansion through very rapid evaporation was taken to the limit. Already, this temperature was unique in the universe, for the temperature of the cold interstellar space is about 3° above absolute zero.

At 0·7° above absolute zero, nearly all of the random motion of atoms as a whole has disappeared. Any further fall depends on stilling the secondary random motions. In 1926, Debye and Giauque independently suggested one such motion for consideration as a means for producing a further fall.

Many substances which are not themselves magnetic exhibit magnetic properties when suspended in a strong magnetic field. When a piece of such a substance is hung between the poles of a strong electromagnet, and orientates itself along the line from pole to pole it is called paramagnetic; when it orientates itself across the line it is diamagnetic.

Each atomic centre, or ion, in a paramagnetic substance has what is called an unbalanced electron-spin, and in fact is a little elementary magnet. Though the positions of these ions are fixed and ordered, their orientations as little magnets are not. They are free to rotate about a fixed centre.

The orientations are completely random. If a strong magnetic field is applied to the substance, then all the little magnets may be oriented

in one direction, producing orderly orientation out of disorderly orientation.

Thus, as the ordering of atoms as wholes can lead to a fall in temperature, the ordering of the sub-motions of the atoms themselves might lead to a further fall.

In 1933 Giauque and de Haas independently succeeded in doing this. A piece of gadolinium sulphate weighing several grams was placed in a bath of liquid helium at about — 1° above absolute zero, and a very strong magnetic field was applied to it. This pulled all the little ionic magnets into line, increasing the order, and doing work which appeared as heat. The temperature of the gadolinium sulphate rose, and then fell, as the heat was absorbed from it by the surrounding liquid helium. When the temperature had fallen again to 1°, the helium was removed, so that heat could not enter from outside into the gadolinium sulphate.

Then the electromagnet was suddenly switched off. Its field disappeared, and the orientated and ordered atoms became free to swing around their point of position as they pleased. They got the energy, or heat, for this from the crystal lattice itself, from the order of atoms as distinguished from their orientation. Hence the temperature of the crystal fell still further, to about 0·5°.

In 1939 Ashmead at Cambridge demagnetized a piece of copper ammonium sulphate in this manner, in a magnetic field of 50,000 gauss, and attained a temperature of about 0·002° above absolute zero.

It may be possible to get down to 0·0003° by this method. It is conceivable, however, that yet other still more subtle motions connected with the nucleus of the atom will be made the means for achieving a yet further fall, perhaps down to one-millionth of a degree above absolute zero.

Yet, however close the physicist gets to absolute zero, his goal always recedes yet further into the infinite distance. But he will never give up the advance. Very low temperatures reveal those fundamental features of matter which are masked by the random, heat movements of atoms. When these are removed, properties which were otherwise unobservable will become evident. It is certain that until these have been discovered, many at present inexplicable properties of matter in bulk at normal temperatures, with which we have to deal in ordinary conditions, will at last be explained. It is as if, at ordinary temperatures, we cannot see the trees for the wood. At very low temperatures, each tree becomes observable in detail. When we have discovered all these details, this deeper knowledge enables us to explain things about the wood, which we could never have done if we were acquainted only with the wood alone.

Thus the search for absolute zero becomes a major clue, perhaps the major clue, to the understanding of ordinary matter as it exists around us.

XI

CROPS AND LIVESTOCK

If man had been born into a world in which the climate was always genial, the soil for ever fruitful, and the vegetation plentiful and varied, or if he had been permitted to stay in the Garden of Eden, he might have avoided labour. The original man on the earth worked because he was hungry, and also, perhaps, because he was cold. He slew such beasts as he could with primitive weapons, clothed himself in their skins, ate the flesh, and varied his diet with fish or fowl, and fruit and roots from the primeval forest. So long as he was a more or less solitary wanderer, these supplies did not fail him. But as the family or small group grew into the tribe, and more mouths were to be fed, food had to be collected from a wider area and stored in the form of flocks, and herds, and granaries. Instead of hunting and killing his meat when he wanted it, he kept it alive in captivity; and instead of searching for and seizing fruits and roots as hunger assailed him, he conceived the idea of growing them near his abode. In this way arose the Agricultural Arts, upon the practice of which every man depends for his food and clothing.

In order to satisfy these needs, flint instruments were replaced by those of copper and iron. Iron, in turn, helped man to obtain more fuel and more iron; the latter gave him the steam engine; the steam-engine developed manufacture, and manufacture made greater demands upon agriculture to supply the raw material by which so many of the later wants of civilization are satisfied. The concentration of people in towns and their employment in the manufacture of goods threw the burden of providing food upon the shoulders of fewer men, without whose labours no manufacture could be carried on. Agriculture is therefore called the mother of industries, and still claims the larger share of human energy, human knowledge, and human skill. Even in highly-industrialized England, importing half her food, it is the largest occupation.

If the term Agriculture is used in its broadest sense it includes the

tilling of the soil and the cultivation of all the plants which yield material for food or manufacture. The cotton fields of the United States and Egypt, the rubber, coffee, cocoa, tea, and banana plantations of the tropics, the fruits of temperate and sub-tropical climates, timber, flax, hemp, jute, and the numerous plants that are grown for their fibre, and the cereals or flowering grasses which in so many instances form the staple food of man are all included. Flocks and herds are usually omitted because except in densely populated countries where every inch of ground has to be utilized, and where the demands of large towns render it profitable, pastoral and agricultural pursuits are each confined to more or less separate areas.

The history of England shows in a striking way the effect of manufacture upon agricultural practice. From the time of the Norman Conquest or earlier the land was cultivated in open fields, in which each man had a share, and to the labour on which all contributed, except the lord of the manor. In the sixteenth century much of the land was enclosed by the landowner and used for wool production, and the remainder became less productive and less capable of producing the food that the nation required. From the middle of the eighteenth century further enclosures took place, so that within another hundred years the open field system had entirely disappeared from the English landscape. But this time the movement was accompanied by improved methods of cultivation. Large farms arose, the small occupier was driven to the wall, and new systems of farming, more expensive, but capable of yielding a higher return from the soil, came into being. Still, no possible methods could produce the food necessary to maintain the growing population, and instead of remaining an independent self-feeding community, Great Britain is today more dependent upon imported foodstuffs than any other country in the world.

The problem of economical and successful home farming, then, is one of profound importance, and the soil which has yielded so generously of its fruits during the centuries in which the nation was being created, has now to be cultivated with that skill and foresight which scientific knowledge alone can supply. In a country so thickly populated, and with so many of its inhabitants engaged in mining, manufacture, transport, and their attendant services, every acre of land is a precious possession, and must of necessity bear a heavier burden than the virgin soils of the vast plains of North and South America that have more recently been brought under the subjection of man. During the last fifty years the knowledge obtained as to the relation between plants and the soils in which they grow has shed a new light on the operations of the oldest of industries, and we shall now proceed to examine in brief outline some of the more striking discoveries on which modern practice is based.

THE FOOD OF PLANTS

The improvements in English farming to which reference has been made, were based on a recognition of the facts that plants require food like human beings, but not upon any exact knowledge of the constitution of this food nor of the mechanism by which it was obtained. Observation had shown that the soil on which a crop had been grown for a number of years became less fruitful, and that its productiveness could be regained by allowing it to lie fallow or idle for a year, or by growing different crops in rotation. The order of the rotation was the result of experience, and so also was the use of farmyard manure to restore the impoverished soil to its former condition, or to increase the yield of the crop on fertile soils.

It was Boussingault who found that plants absorb carbon dioxide from the air and not from the soil, and the great German chemist, Justus von Liebig, who emphasized the discovery in a report to the British Association for the Advancement of Science in 1840. The gas enters the plants through minute openings, called stomata, in the under surface of the leaves and, under the influence of sunlight, the carbon is appropriated and the oxygen is evolved. During the night this process ceases. It was known, too, that the roots absorb water from the soil, and with it any substance that the water holds in solution. In this way they obtain their mineral constituents, consisting chiefly of lime, potash, and phosphorus compounds together with more complex bodies containing nitrogen.

The interior of a plant is a miniature chemical factory, taking in material from the air and soil, and building up with marvellous regularity and precision the complicated substances which determine its constitution. Among its products are timber, fibres, sugar, aromatic essences, perfumes, deadly poisons, healing drugs, and dyes that rival the rainbow in hue. The vegetable world, using throughout substantially the same raw materials, but in different proportions, specializes its manufactures, each workshop, from the oak to the microscopic fungus, concentrating its energy upon a limited but characteristic series of finished goods. The only condition imposed is that the raw material shall be supplied in a soluble form so that the root hairs can convey it into the system. No matter how rich the soil may be in the elementary constituents necessary for growth, if these are not in a palatable and digestible form they are useless for the end in view.

A chemical analysis of the plant will reveal the relative quantities of the various materials that are required for its growth, and manuring consists in supplying to the soil just those materials that are necessary to supplement the amount which is available, and which have been found to be necessary for the maximum yield. From the time of Liebig

it has been recognized that potash and phosphorus compounds are necessary, and their effects have been fully well understood, but the theory of action of nitrogen compounds was for long a subject of acute controversy. This, however, and many other problems of cultivation have been solved by the long series of experiments which have been carried on in Rothamsted and other experimental stations.

It has been established in the case of wheat that potash gives increased vigour and power to resist drought, damp, and rust, while phosphatic compounds promote root development in the early stages, and hasten ripening at a late period in the life of the plant. Nitrogenous manures encourage leaf growth and the attainment of vegetable maturity; without nitrogen there is no progress beyond the seedling stage. A certain plot of ground on the station at Rothamsted has grown wheat continuously for a century, and still produces 13 bushels per acre. If a manure containing all the necessary mineral constituents but without nitrogen is added the yield is only increased to 15 bushels. The use of a nitrogenous manure alone raised the yield to 21 bushels, and the addition of both the mineral and nitrogenous manures to 35 bushels. These facts are illustrated in Plate XXX.

Of all the manures used by the farmer those containing nitrogen are the most costly and remain for a shorter time in the soil. Some of the mineral substances such as superphosphate, basic slag, etc., serve for more than one season, but the nitrogenous manures are decomposed or washed out by the winter rains.

Let us then review the various ways in which nitrogen required for growing crops is supplied to the soil. The ammonia, nitrous and nitric acids which are found in rain water, and which have been supposed to be formed by electric discharges in the upper regions of the atmosphere, provide an infinitesimal fraction of the amount required by the vegetable world. The vast ocean of nitrogen in the air, which amounts to 33,000 tons per acre, is not, except to a small extent in a way to be described later, capable of being assimilated directly by plants. The amount of animal and vegetable refuse containing the nitrogen which has been abstracted from the soil is limited. The ammonium sulphate obtained as a by-product in gas and coke manufacture might be very largely increased in amount. Here the nitrogen from the plants of the carboniferous age is being used to nourish and sustain their descendants.

While the decay of animal and vegetable matter does yield some return to the soil, this return is neither immediate nor complete. Some artificial manuring is necessary sooner or later even with virgin soils, and nitrogenous manures are the most expensive which the farmer has to buy. For many years the chief sources were the guano beds in certain islands of the Pacific and in Peru, and the beds of sodium nitrate in Chile. Guano is the excrement of countless generations of sea birds.

It is only found in certain areas, and in limited amount. The Chile 'saltpetre' beds were in all probability formed by the drying up of a large lake which, occurring in a rainless district, left behind great deposits of salts which would ordinarily have been washed away. In several other parts of the world there are similar tracts of desert in which the soil is impregnated with salts of sodium and potassium, and where the absence of water has proved a great obstacle to exploration. The present production of the Chile beds is at the rate of 1,700,000 tons per annum (it was 1,500,000 tons in the 1951–2 season). Nearly all of it is used as a manure. (It should be observed that these beds, until atmospheric nitrogen became available, were the chief source of supply of nitric acid, which is prepared by acting on sodium nitrate with sulphuric acid, and of iodine.) The possibility that these deposits might be exhausted within a generation gave pause to those who study the conditions under which food is produced and the rate at which the demand for it is increasing.

This was the position when in 1898 Sir William Crookes in his Presidential Address to the British Association sounded a note of warning.

It is characteristic of our age that the solution proposed by Crookes should be an accomplished fact within five years or so of its announcement. The nitrogen in the air can be caused to combine with the oxygen by burning the two gases in the flame of an electric arc. Calcium nitrate can be obtained from the compound formed. Birkeland and Eyde established this process in Norway on a commercial scale. Again, in Chapter X it is shown how the nitrogen, which is an otherwise useless by-product in the manufacture of oxygen by Linde's process, is passed over calcium carbide and converted into an available plant food called nitrolim. There are yet other processes, and it is clear, now that the main and well-nigh inexhaustible reserve store of nitrogen has been tapped, that it is possible to recoup the earth for the depredations of former years.

THE BIOLOGY OF THE SOIL

The application of artificial fertilizers is, of course, only a means of increasing productiveness, and though the general principles upon which successful cultivation depend have been established by centuries of practice in the agricultural arts, it is only within recent years that a real insight has been obtained in the secrets of fertility. Beyond the breaking up of the surface to enable air to obtain access, and to provide a medium into which the roots can penetrate freely, and draining to prevent accumulation of stagnant water, there is now a vast amount of information about the changes which the materials undergo, and the

causes to which they are due. A soil may contain all the necessary elementary constituents of plant food and yet be unfertile; it may lose its fertility temporarily by over-cropping and regain it by lying fallow, by bearing another crop, or by the addition to it of materials in which it is deficient. What, then, are the processes by which plant food is manufactured in and below the surface of the ground?

Generally speaking, a soil may be regarded as a mass of inert mineral matter containing about 15 per cent of water. The water contains certain mineral substances which it has dissolved, and the particles of soil in varying size form a framework over which the solution spreads as a thin film. Apart from the water there may be 80 per cent of mineral matter and 5 per cent of organic material—the decaying remains of vegetable and animal life. We have already seen that except for the infinitesimal amount of nitrogen compounds which falls with rain, and that which is added by the cultivator, the main source of nitrogenous food is the organic matter in the soil. The fertility depends largely, therefore, upon the decayed animal and vegetable material which accumulates in or is added to the land.

Many years ago Pasteur showed that the soil contains bacteria—minute forms of vegetable life—which may exist in such numbers that they produce profound and far-reaching chemical changes in the material in which they live. Their size is about $\frac{1}{1000}$ of a millimetre or $\frac{1}{25,000}$ of an inch. They multiply under suitable conditions with extraordinary rapidity, one dividing into two every 35 minutes, so that at the end of 12 hours one bacterium may have 12,000,000 descendants. A cubic inch of soil may contain several hundred millions of them. And in addition to these there are other lowly microscopic forms of vegetable life, such as fungi, and protozoa or similarly small members of the animal kingdom. We have to deal, therefore, not with a mixture of substances such as is ordinarily examined in the chemical laboratory, but with a teeming population living, working, dying, competing for nutriment, breaking down the material in and on which they dwell, and effecting changes which are so numerous and complex that it almost passes the wit of man to unravel them.

The first suspicion that certain changes in the soil were biological rather than chemical arose in 1878. It was known that as a rule the form in which nitrogen is most easily assimilated is that of a nitrate, and that if ammonium salts are added they are rapidly converted into nitrates. When, therefore, it was found that nitrification, as the process is called, did not start immediately in an artificial soil, but required 20 days for commencement, it was suggested that the change depended upon the growth and multiplication of some form of life. And in 1887 Winogradsky and Warrington, independently isolated the microbes responsible for the work.

The change takes place in two stages, each due to the action of a particular bacterium. One converts the ammonia into nitrous acid and the other converts the nitrous into nitric acid. Neither of them is able to effect the complete conversion; they must work in co-operation.

Ten years later another variety of the microscopic flora of the soil was discovered to serve a further purpose. The roots of plants belonging to the order leguminosæ, comprising, among others, peas, beans, clover, and vetches, possess nodules (Plate XXXI*a*) on their roots, and these nodules were found to contain colonies of bacteria (Plate XXXI*b*) capable of absorbing nitrogen from the air and converting it into protein for the use of the plant. They feed their host in return for a habitation and a home.

In contradistinction to the *nitrifying* organisms first described, these are called *nitrogen-fixing* bacteria. The same or a similar variety has been found on the roots of forest trees, and some are also found free in the soil. There is, in addition, a third form which in some way decomposes nitrogen compounds, producing free nitrogen which escapes into the air, and helping to maintain that uniformity of composition which is one of the most important and striking properties of the atmosphere.

During the last forty years this underground society has yielded up still another of its secrets. Instead of working in apparent harmony and co-operation it would appear that some of them prey upon the others. In 1888 Frank showed that if soil was heated to 130° C. its productiveness was decreased, but that if the temperature was not more than 100° C. its productiveness was more than doubled, and the soluble constituents were increased. Five years later Hiltner and Sturmer showed that treating the soil with carbon bisulphide altered the microscopic flora. The number of bacteria which could be counted decreased by 75 per cent, but when the carbon bisulphide had evaporated their number increased until they became more numerous than before. At a later date toluene and other substances were found to have a similar effect.

The question was pursued by Russell and Hutchinson of the Rothamsted Experimental Station. A microscopic examination of the soil before and after heating or other treatment showed the presence in the former case of protozoa, algæ, fungi, and other low forms of life, which were absent after heating or other treatment. The protozoa are extremely minute members of the animal kingdom, and two varieties which are recognized—*colpoda cucullus* and *amoeba nitrophila*—are known to devour bacteria. The algæ and fungi may also operate in other ways which are unfavourable to the growth of more useful forms of vegetation. But if the protozoa are killed then the bacteria can increase, and so far as these are concerned in the manufacture of plant food, the soil will gain in fertility.

The introduction of animal and vegetable refuse into the soil, therefore, benefits it in two ways. Part of it is converted into carbon dioxide, ammonia, water, and nitrogen, and part tends to accumulate, increasing by its texture the power of the soil to retain moisture. Some of the ammonia is absorbed by the clay constituents of the soil, forming a curious compound the nature of which is not yet known, and some of it is converted by the nitrifying bacteria into nitric acid. Part of the carbon dioxide is assimilated by the bacteria and other forms of plant life in the soil, and part escapes into the atmosphere to suffer a similar fate. The nitrogen is attacked by the nitrogen-fixing bacteria or escapes.

Russell divided the microscopic life into three groups:

(*a*) Saprophytes, which live on and decompose organic matter.

(*b*) Phagocytes, which devour living bacteria.

(*c*) Larger organisms, which in other ways than (*b*) are inimical to plant growth.

Raising the temperature of the soil to 98° C. or treating it with carbon bisulphide, toluene, or other substances kills the members of groups (*b*) and (*c*) and allows the members of the group (*a*) to increase and do their beneficial work more vigorously.[1]

The tendency in uncultivated lands is for nitrogen compounds to accumulate. Clearing and ploughing let in light, air, and rain. Some of the carbon dioxide and ammonia escape, and much of the soluble nitrogenous material is washed out of the soil. Deterioration goes on in new countries in all cases until wheat is displaced by rotation of crops. The exhaustion of the soil is not produced merely by the wheat crop, but also by the method of cultivation altering the microscopic flora of the soil and destroying the natural balance of food supply and food demand.

On so-called sour land there are doubtless other influences than those we have outlined at work. In the absence of calcium carbonate the decomposition of organic matter may produce poisonous substances which hinder plant growth, and lack of fertility may be due to this cause rather than to lack of available food. But in the main the explanation which has been given is in accord with the greatest number of facts. It will be clear, however, that we are only on the threshold of a vast field of knowledge, the existence of which has been revealed by a glimpse into the underground world of the animal and vegetable kingdom. When the old agriculturalist spread manure over the land and grew his crops in rotation, he knew by long experience that the results would be good; but he was profoundly ignorant of the fact that he was altering the balance of microscopic existence down in the corridors and caverns of the soil. He did not realize that just as the highly organized plant he tended with such care built up from the materials in the air, and about its roots the food, medicine, or fibre it required, so

[1] The bacteria are killed, but not their spores.

also the more lowly forms of life were busy preparing for consumption the food to be enjoyed by the aristocratic giants of their race.

THE PHYSICS OF THE SOIL

From 1830 to 1880 the problem of fertility was regarded mainly as one of Chemistry. It was thought that if the mineral matters which plants abstract from the soil were provided in sufficient quantity and in a more or less soluble form, crops would flourish year after year in the same ground. The next stage was recognition of the influence which low forms of life such as bacteria, fungi and protozoa have upon the growth of larger plants, and consequent development of the biological theory of fertility which has been described. At the same time it was understood that these were only two aspects, and that a number of causes are necessary to explain the facts of experience in different climates and on a variety of soils. For example, growth is most vigorous between certain narrow limits of temperature, and conditional entirely upon a certain minimum supply of water; while the production of available food material by bacterial agency is again dependent upon temperature and does not occur in a water-logged soil. Consequently much attention has been given in recent years to investigation of the conditions which favour the retention of heat in the soil and which control the water content and drainage.

If a narrow glass tube is dipped into water or any liquid that wets the surface, it rises to a higher level inside the tube than outside, and the narrower the tube the higher the water will rise. In the case of mercury, which does not wet glass, the level inside the tube is depressed. This capillary elevation—so-called from *capillus*, a hair—is due to surface-tension. The free surface of every liquid is stretched. Consequently a drop, falling freely, always assumes the shape of a sphere, because a sphere has a smaller surface than any other shape for a given volume. This surface behaves as though it were an elastic skin, and it is not difficult to see why this should be so. There must be some force which holds the particles together or the liquid would fall to pieces. And it is easy to understand that while the particles inside a liquid are pulled equally in all directions, those at the surface are attracted inwards. They are held more firmly than the internal particles, they resist separation, and a needle will rest upon the surface of the water, though once it breaks through it sinks.

Again if a marble or other object is suspended by a thread, dipped into water and then lifted out, it will be seen to be enclosed within a film, and all that can be removed by shaking is the surplus drop at the bottom.

Now the soil must be regarded as a number of particles of varying

size with tiny capillary spaces between them. Movement of water within the soil takes place along these passages, and water is retained in thin films on the surface of the particles even when the passages are empty. If the soil is sandy it drains well and water rises freely in it provided the particles and therefore the pores are small. But for that reason it also loses water readily by evaporation, and crops upon it will suffer in a dry season. Further, since dry soil requires much less heat to raise its temperature than wet soil, such a soil is warm and will raise an earlier crop than a wet clay soil. On the other hand, a clay soil, being more retentive of moisture for reasons which will appear later, will support growth to a later period in the autumn.

The ancient practice of breaking up the surface-soil during the growing season has a scientific explanation. The liquid film which, in a firm soil, may be regarded as continuous, is broken and evaporation is checked. Moreover, the dry particles separated by air spaces form an excellent non-conductor and keep the soil about the roots at a uniform temperature. If any rainfall is to be beneficial during a severe drought, it must penetrate this dry surface layer to the soil below. Failure to do this is the cause of crops wilting even after a shower; and it is obvious that if a watering-can has to be used in the garden it should be used thoroughly.

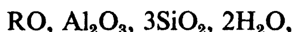
Part of the water which falls as rain sinks into the ground and runs into wells or drains away; part is evaporated directly from the surface; part goes to form root and stem, leaves and fruit; and part is transpired. The amount transpired is on the average 300 lb. for each pound of dry vegetable matter produced. It follows, therefore, that a vast quantity must be required per acre—more in fact than is available from the annual rainfall in some districts. Wheat, for example, transpires a 6-in., and mangolds a 10-in. rainfall. Some land will not support continuous cropping. But in the semi-arid regions of the United States and Australia a plan of dry farming has been developed, based on the practice in the relatively dry counties of the south and south-east of England. When the land is bearing a crop the surface is frequently stirred in order to conserve the moisture, and the land is allowed to lie fallow for one year in two or three in order to accumulate a year's rainfall in the soil.

Unfortunately the whole of the moisture in a soil is not available for the use of the plant. A crop begins to wilt while a certain percentage of water remains. This quantity may be only 1·5 per cent in sand, 10 per cent in clay, and as high as 40 per cent in peat. The 'free' water available for plant growth is that contained in the pores or capillary spaces; the 'hygroscopic' water exists as a film which surrounds the particles, and in all soils equally dry this film is about 0·00003 in. in thickness. But the problem of water-retention, of texture, and of other factors is complicated by the fact that all soils except the loose sands contain

colloidal substances [1] which 'adsorb' or attract moisture (and solutions) to their surfaces. In fact, the film which surrounds the particles is generally a colloid of the 'gel' class, the members of which are capable of taking up and holding strongly considerable quantities of water. The readiness with which some of these bodies pass from the colloidal to the flocculent condition and *vice versa* in the presence of other substances which do not, in the ordinary sense, exercise a chemical action upon them, explains two very important facts which have long been known. These are the power of a soil to retain certain soluble salts used as fertilizers, and the bad effect which certain salts exercise upon the texture of the soil to which they are supplied. Thus all ammonium salts and organic compounds of nitrogen are retained—i.e. they do not pass out with the drainage water. In the case of the ammonium salts it is the ammonia which is adsorbed, and the liberated sulphuric acid attacks the calcium carbonate in the soil, and converts it into soluble sulphate which is washed away. The result of continued applications of ammonium sulphate to a clay soil is to remove the calcium, which as bicarbonate is effective in keeping the clay particles in a flocculent condition.

Again, other salts, such as potassium sulphate and sodium chloride, either have an alkaline reaction or undergo changes in the soil which result in the formation of alkalis. The effect is to deflocculate the clay, and to create a colloidal condition with a close texture which is unfavourable to plant growth. For that reason a mixture of potassium sulphate and ammonium sulphate is better for clay land, because the influence of the one upon texture neutralizes that of the other.

The removal of calcium carbonate from the soil which is inevitable with the potash and ammonium fertilizers is due also to a very interesting reaction which occurs in the soil owing to the presence of zeolites. A zeolite would be described by a chemist as a hydrated double silicate of aluminium and an alkali or alkaline earth metal; but it is no worse for that. The zeolites are the result of weathering upon the mineral felspar in igneous rocks. They have the general formula



$$RO, Al_2O_3, 3SiO_2, 2H_2O,$$

where R stands for Ca, Mg, K_2 or Na_2. If the zeolite contains calcium it has only to be placed in a solution of sodium chloride in order that sodium shall replace calcium in the mineral. Similarly, if the sodium compound is exposed to calcium chloride solution the calcium goes back home and the sodium comes out. It may be noted in passing that the permutite process for softening water consists in removing calcium compounds by means of a sodium zeolite. There seems to be no doubt that calcium is removed from soils in this way.

[1] See Chapter XII.

But these are only a few amongst the hundreds of facts which have accumulated from the patient labours of agricultural chemists in many parts of the world.

PEDIGREE WHEAT

When man is faced with a big problem like that of the world's supply of wheat, he is not satisfied with a successful attack in one direction, but must needs seek other ways of extending his power and dominion over Nature. He knows that there is not one variety, but many varieties of wheat, and that a fertile soil, cultivated by the most enlightened methods, cannot produce either the greatest quantity or the highest quality from an inferior strain of seed.

For the sake of simplicity the matter may be considered from two points of view—quantity and quality. Forty years ago, the fact that supply was not increasing so rapidly as the demand began to give serious concern. The opinion was expressed that with existing varieties and methods of farming the wheat-growing areas of the world would, sooner or later, be taxed beyond their capacity.

Such a result could only be deferred for a time by the use of artificial fertilizers. For, in addition to suitable food, the wheat plant requires a stiff soil to support its long stem, a wet season of growth, and a warm dry period in which to ripen—conditions that are only found in certain regions of the globe. In many other districts the soil might be suitable, but the summer is too short or too wet, so that the grain would not ripen, or the disease called *rust* would make its appearance. The fact, however, that existing varieties have very definite requirements does not mean that other varieties, less fastidious in their needs, are unobtainable. All those that are grown now—and their name is legion—have developed from four which flourished in olden times, and where there has been so much change there is possibility of more.

Consider now the question of quality. Everyone knows that some varieties of flour are better for baking than others, because they make a larger and better shaped loaf, and it has long been the practice to ascertain the quality of flour by an actual baking test before purchase. The theory of baking itself is not without interest. Flour consists essentially of three constituents—*starch*, a gummy substance known as *gluten*, and about 1 per cent of *sugar*. When it is mixed with water, and *yeast* is added, the latter feeds on the sugar, producing carbon dioxide, which fills the mass of dough with small bubbles. The heat of the oven causes these bubbles to expand, and the final result is a light spongy framework of hardened gluten impregnated with grains of starch.

The sugar is formed from the starch by the action of a ferment called diastase, which appears to exhibit varying degrees of activity in different

varieties of flour. The amount of sugar is fairly uniform, and when this has been used up by the yeast, the production of a further quantity of gas is dependent upon the action of the diastase in manufacturing more sugar. If the ferment is active, the yeast grows quickly, produces a large volume of gas, and makes a big loaf. But if the ferment is sluggish, the production of gas is slow, and a small loaf results. T. B. Wood has shown that the amount of gas evolved in a given time furnishes a very good guide to the size of loaf that will be produced, and he has devised a method of testing the baking strength of flour which can be performed on the grain from a single ear.

But the size of the loaf is only one aspect of strength, for shape and texture are of considerable importance, and these depend, not on the diastatic fermentation of the starch, but upon the character of the gluten. All attempts to trace the result back to the chemical properties of gluten have failed. It is one of those curious substances known as colloids, the physical properties—appearance, texture, etc.—of which are profoundly modified by the presence of small quantities of acids or salts. It occurred to Wood, therefore, that the variable character of the gluten in different kinds of flour might be due to the presence of a particular acid or salt in the grain. The final result of his work is to indicate that the shape and texture of the loaf are closely connected with the presence of phosphates, which are found in larger quantities in strong than in weak wheats

The result of unravelling the meaning of the term 'strength' has been that millers and bakers have taken steps to confer upon weaker wheats those properties of strength which they so much desire. Malt extract, for example, contains an energetic diastatic ferment and, by spraying it over flour, the rate of formation of sugar, and therefore of gas, is increased. And in the other direction, certain phosphates are being mixed with flour in order to secure the shape and texture that brings the largest trade.

But to return to the main problem. Hardier, earlier ripening disease-resisting forms of wheat, producing a strong flour, are clearly desirable, and to these ends many minds are being directed. The problem is of peculiar importance to this country because English wheats lack strength, and have to be mixed with a hard Canadian or other variety for which a higher price is paid. It is of importance to the world at large because it is estimated that the loss from rust alone is equal to one-third of the world's harvest. So the farmer, who has long recognized the importance of pedigree in cattle and sheep, has now realized the importance of plant breeding in enabling him to supply the workers in mines, in factories, and in transport with food.

It has already been remarked that the breed of wheat is generally mixed, and it follows that valuable land, manure, and labour are being

expended upon varieties which yield an inadequate return. Out of this fact two separate problems arise—one is to replace the inferior by superior varieties, and the other is to improve even the superior varieties themselves. The first problem is mainly one of selection. A variety that possesses the requisite qualities is singled out and seed is sown. As the plants arrive at maturity seed is gathered, sown in the same way as before, and again used to increase the stock; and when sufficient has been accumulated, it is distributed to farmers, who discard the varieties upon which they have hitherto depended.

Until the last forty years the practice of plant breeding was carried on by the method of trial and error, and occasional success was a small oasis of comfort in a vast desert of failure.

During this century, however, plant breeding has made great strides in many countries. The late Sir Rowland Biffen, of Cambridge, produced valuable new varieties by the hybridization of wheat. He collected varieties of wheat from all parts of the world, grew them, and crossed those which seemed to possess features which would be desirable in combination. In this way he succeeded in producing, amongst others, two varieties 'Yeoman' and 'Little Joss', the one having the same valuable baking quality as the hard wheats of North America, and the other unaffected by yellow rust. 'Yeoman' has produced in this country a yield of 96 bushels per acre—which may be compared with a world's average of thirteen. T. D. Lysenko and his pupils in the U.S.S.R. have raised again the question of the relative roles of 'nature' and 'nurture' in heredity. Quality seems to depend in some way upon soil, and the hard wheat of Manitoba does not reproduce its characteristic property when grown on the manured land of England. Many workers are engaged upon this and similar problems.

ANIMAL NUTRITION

Systematic research on nutrition began rather more than a century ago, largely under the stimulus of Liebig, and has led to a very much deeper understanding of the quantitative aspect of the subject. Today, a great deal of precise knowledge of the quantities of different kinds of food required to preserve good health is available. It is known how much fat, carbohydrates such as sugar and starch, proteins such as meat, must be consumed if a person is to perform certain kinds of work. During the last fifty years, much progress has been made, in addition, in the qualitative aspects of nutrition. The discovery of vitamins showed that a man, or any other living organism, must obtain from his food, besides sufficient quantities, many substances which enable his body to assimilate these basic quantities and building material. The vitamins are present in too small quantity to be themselves a fuel for the

organism. They are more like minute but vital parts of the building machinery.

The quantitative and qualitative aspects of nutrition just mentioned, have had a tremendous effect on social and agricultural policy. When precise causes of bad nutrition were discovered, it became obvious in many cases that there was no good reason why they should be allowed to continue to exist. Governments and municipalities began to take action to ensure that malnutrition should be eliminated, both among human beings and domesticated animals. It was wrong that human beings should not be properly fed, and it was unprofitable to feed animals badly.

The outcome of this work on nutrition, pursued in many countries, is reflected in the human field by the modern attention to milk and fruit juices for children, the provision of school meals, and attempts to establish better food habits.

It is reflected in the cultivation of plants and animals by a far more scientific control of fertilizers, and animal feeding. The food properties of crops and grasses are more precisely understood, and the good husbandman is no longer satisfied with giving his animals just fodder, but is more concerned with kinds, quantities and qualities.

One of the outstanding centres for the study of nutrition is the Rowett Research Institute at Aberdeen, in Scotland. This arose from a scheme for promoting scientific research in agriculture, which was adopted in 1911 by the Development Commission. Its original governing body was set up in 1913, and consisted of an equal number of members nominated by Aberdeen University, and the North of Scotland College of Agriculture. In 1914, this governing body appointed Boyd Orr, then a lecturer in veterinary physiology at Glasgow University, to begin a scheme of research in animal nutrition. The Institute had no building, and Boyd Orr was given temporary rooms in Marischal College in Aberdeen University. However, the First World War intervened, and Boyd Orr joined the Royal Army Medical Corps. He served for four years, with great distinction and gallantry. After the conclusion of that war he returned to the Institute. Land and finance for a building were donated by J. Q. Rowett, and central buildings were opened in 1922. An experimental stock farm of 600 acres was given to the Institute in memory of the famous Shorthorn Cattle breeder William Duthie of Collynie. The Aberdeen region is one of the chief centres of cattle-breeding in the world. The presence of the great traditional knowledge of this art is one of the conditions which make Aberdeen such an excellent centre for agricultural research.

The farm is run as one unit with the 400-acre farm of the North of Scotland College of Agriculture. The library, founded by W. A. Reid, was accommodated in a large new building in 1938. In this building

the Commonwealth Bureau of Animal Nutrition is housed. It is the chief clearing-house of British countries for information and literature on human and animal nutrition. In 1933, a hostel was opened for research workers, especially those from overseas parts of the Empire. It serves also as a club for the staff of the Institute.

Under Boyd Orr's direction, the Institute became world-famous. Besides stimulating research in many directions, Boyd Orr brought the implications of the results of nutrition research to the understanding of great numbers of people. He retired from the directorship in 1945, and became the first Director-General of the Food and Agriculture Organization of the United Nations, where he continued his work of education on nutrition on a world-scale. He presently was awarded a Nobel Prize.

The tradition established by Boyd Orr has been given a new and brilliant extension by R. L. M. Synge. He is the head of the department of protein and carbohydrate chemistry. He was jointly awarded the Nobel Prize for chemistry, with A. J. P. Martin, in 1952, at the age of thirty-eight, for work on the development of partition chromatography. This method has greatly increased the possibilities for investigating the chemistry of proteins, which have a fundamental role in living processes.

Synge and his colleagues are applying the new techniques of analysis to the biochemical processes taking place during digestion. Their aim is to go beyond the mass-processes of digestion, in order to elucidate its inner mechanism. The main question is not what protein, carbohydrate, fat, in general change into, but rather how, and in detail.

The attitude of mind established in agricultural chemistry by Liebig more than a hundred years ago is still dominant. The agricultural chemist still thinks and talks in terms of the analysis of 'proximate principles'. The most important task today is to go beyond the 'proximate principles' and find out in detail the fundamental chemical and molecular mechanisms underlying processes, which has become possible through the advances of modern scientific knowledge and chemical techniques.

Synge's physiological colleague A. T. Phillipson secures from the stomachs of ruminants, such as sheep, specimens of material in process of digestion. Synge then analyses them by the new techniques. It had previously been assumed that the physiology of animal digestion was closely similar to that of human digestion, and had been described in terms of the ideas worked out through investigations of human physiology. Synge and his colleagues have found that when animal digestion is examined closely, its processes are found to be very different. Consequently, nearly every experiment is revealing something new.

He is aiming at the correlation of the biochemistry of animal digestion with that of the plant, so that the efficiency of plant crops for animal

food can be determined not only by the quantity of crop produced for a given effort, but also by measuring its biological value to the animal. For instance, it is possible to increase greatly the amount of grass which can be cropped from a pasture, by cultivating it according to new methods, ploughing it up and replanting it with specially selected grass seed. But it is not definitely known whether these special strains of grass make as good food for the animal as the mixed grasses from the old pastures. The refined assessment of food values depends on the improvement of the chemical analysis of grass, and of what goes on in the ruminant's stomach.

In the rumen food proteins are decomposed by microbes, with the production of ammonia. The ammonia probably decreases the food value of the remaining protein, and attempts are being made to investigate the effect in detail. It is of great importance in relation to the high protein diets given to dairy cows. Parallel with this investigation, the non-nitrogenous substances produced by the breakdown of proteins is being studied. The chief products are carbon dioxide and volatile fatty acids. Special attention is being paid to the effects of different methods of conserving grass crops and fish products on their value as food for ruminants.

The nature and fate in the rumen of the carbohydrates, the sugars and starches, derived from grass, are being determined.

Besides following the chemical changes in the animal, they are analysing the nitrogen constituents of grass and other fodders, and of the micro-organisms in the rumen. The latter information is being used for establishing criteria for determining the numbers and nature of the rumen micro-organisms. It seems, for instance, that ae-diominopimelic acid occurs only in bacteria, and that different species contain differing, and characteristic amounts of it. Synge has shown that y-amino-butyric acid is a major constituent of grass, and he is determining the exact nature of peptide-like substances in grass juice.

A. E. Oxford is investigating the role of the protozoa in the fermentation which takes place in the rumen. He aims to escape from the attitude of the old investigators, who asked the question as to whether they were helpful or harmful to the host. They are now being treated as inevitable and individual fermentative agents, just as yeasts might be in making bread.

These are some of the fundamental researches which are leading to the next revolution in the chemistry of nutrition. The new attitude of mind and conception of the subject are as important as the rich flow of new chemical and biological facts which are being collected daily.

Under the programme of applied biochemistry, J. Duckworth is investigating how far economies can be made in the use of conventional

animal by-products, such as meat-meal, fish-meal and dried skimmed milk, in poultry rations. It appears that the essential function of these additions to the diet of corn or cereals is to provide vitamin B_{12}, riboflavin, and proteins rich in lysine, cystine and methionine.

Alcali-reduction meal, prepared from excess herrings from gluts, was found to be of low value for chicks. It was found that by modifying the process in the light of this knowledge, a better meal was obtained.

A long-term study of the calcium and phosphorous metabolism of sheep on hill-farms is in progress. The nutritive value of roughages from hills is being compared with their chemical composition. These studies aim at an improvement of the efficiency of the large amount of hill sheep-farming in Britain.

D. E. Tribe is applying the method of the naturalist to the study of the behaviour of sheep in the pasture. Just how do they eat, and select their food. Is appetite behaviour a reliable guide to physiological need? Much is known about grass, but little about the ways of grazing animals, and they are trying to find out more by continuous watching. How far do smell and taste direct the animal's choice? It is known, for instance, that if a diet lacking vitamin B complex is divided into two parts, and a minute quantity of vitamin B complex is added to one of them, rats are under some conditions able to choose the right one to eat. It is not known how they do this. Nor is the choice infallible. Under other conditions, the rats may choose the wrong diet, and ultimately die as a consequence.

Ten Cheviot ewes kept indoors were allowed to choose from good and bad diets. Only one of them lambed normally. Nine of them apparently ate too much of the bad and not enough of the good.

Continuous observation of cattle grazing out of doors has been carried out to determine the importance of 'browse'. No evidence was found in favour of the belief that weeds are essential to the diet of grazing animals.

Five years of naturalist investigation has led to the conclusion that the behaviour of an animal does not necessarily reflect its nutritional requirements, and it is therefore unwise to base a system of animal management on recorded observations of behaviour.

Howie, Biggar, Thomson, Cook, Naftalin and others have shown that cold and damp housing may damage the livers of suckling pigs. Those reared in a wooden ark in an indoor concrete run developed normally, while others reared in an indoor concrete pen died of a liver disease.

Crichton and others are investigating the effects on cattle of differences in diet during the first two years of life, by feeding experiments on identical-twin dairy cattle.

Such, then, are some of the researches in progress. The various

departments have the assistance of a statistical section for the interpretation of the significance of their results, besides the informational resources of the Library and Bureau.

CHROMATOGRAPHY

The method of chemical analysis named chromatography was invented by the Russian botanist M. S. Tswett in 1906, in order to separate various plant pigments. Its conversion into a major method of chemical research is due to A. J. P. Martin and T. L. M. Synge. They studied bio-chemistry at Cambridge, and became concerned with the problem of the analysis of the chemical constituents of living organisms. In 1938 they were appointed to research posts in the Wool Industries Research Association laboratory at Leeds. They were engaged in the investigation of the proteins which constitute wool fibres. They found that the existing methods of analysing the amino-acids of which proteins consist were unsatisfactory. These depended on the extraction of the amino-acids in bulk. There are numerous amino-acids, and many of them closely resemble each other. The extraction of any particular amino-acid in bulk tended to be a difficult and clumsy process.

Though many of the amino-acids closely resembled each other, their solubility differed. Martin and Synge conceived a method by which the amino-acids could be separated through their differing solubilities, and their separation indicated by colour changes.

They filled a vertical glass tube with silica powder, which is capable of retaining much water. A mixture of amino-acids dissolved in water was poured in the top, and then an organic solvent was added. The solubility of each amino-acid in the stationary water held by the silica was different from that in the solvent moving down the column. Owing to this, each acid distributed itself between the water and the solvent in a particular way, and accumulated in a particular level in the tube. The whereabouts of this level was revealed by an indicator mixed with the silica powder, which produced a coloration.

The acids could be separated by pushing the column out of the tube, cutting off the various levels, and extracting the separated acids by conventional methods.

It was presently found that cellulose was suitable as a supporting material, and in 1944, paper chromatography was introduced.

If a drop of the mixture of amino-acids was put on the top right-hand corner of a piece of blotting or filter paper, washed with a suitable solvent, and then sprayed with an indicator which changed colour in the presence of an amino-acid, then a series of coloured spots appeared along the right-hand edge of the paper. The paper could be turned round so that these spots were now at the top, and they could be washed

with another solvent, producing another series of spots. The various spots contained particular amino-acids, or groups of amino-acids. In one of the early analyses of wool proteins, no less than twenty-two amino-acids were separated from wool protein.

The method has been developed in many ways, and is being used in almost every field of chemistry, introducing a new order of possibilities in analysing small quantities of similar substances. This is particularly important with regard to the chemical analysis of the materials of life. The method is simple and elegant, and does not require much skill.

Partition chromatography, as it is called, is effecting a revolution in chemistry comparable with that caused by Liebig's introduction of new methods of chemical analysis at the beginning of the nineteenth century, and equally great results can be expected from it.

A NEW AGRICULTURAL INSECTICIDE

The advance of chemistry has supplied powerful new insecticides to the farmer. One range of these has been given the name of Gammexane. They are based on benzene hexachloride, a compound which was first prepared by Michael Faraday in 1825. This substance in its ordinary form has some insecticidal activity. But its molecules, while all possessing the same number of constituent atoms of carbon, hydrogen and chlorine, exist in four different arrangements, or isomers. These are named the β, γ and δ isomers. Chemists of the Imperial Chemical Industries separated the four isomers, and tested the insecticidal properties of each isomer. They proved in 1943 that the insecticidal power of benzene hexachloride resided almost entirely in the γ-isomer.

A new series of insecticides based on pure γ-benzene hexachloride has been produced, which are almost entirely harmless in their direct effect on men and animals, but are deadly and lasting in their effects on various insects. They have been found useful against cattle ticks, wireworms and cockroaches, and also against bed-bugs and house flies. They are the most effective insecticide yet found for combating the locust.

HORMONE WEED-KILLERS

The study of the physiology and chemistry of animals and plants has revealed the existence of substances which, though present in very small amounts, have a profound effect on growth. These are the hormones. They are complex substances, many of which have been obtained from animals and plants, and their chemical constitution determined. Subsequently, chemists have succeeded in synthesizing a number of them.

The pioneer work on the hormones concentrated attention on their

growth-promoting and growth-controlling properties. In 1940, biologists at the Jealott's Hill Agricultural Research Station of the Imperial Chemical Industries discovered that if plant hormones were administered in certain strengths of concentration, they could hinder growth. It was observed that the growth of some plants was hindered more than others. This suggested the possibility that a new kind of weed-killer might be discovered, with selective properties, by which weeds might be destroyed while crops were unharmed, or even stimulated. As many of the plants adversely affected were weeds which are common in corn lands, it was hoped to find a hormone concentration which would especially be effective in killing the weeds in cornfields.

Two chemists, W. G. Templeman and W. A. Sexton thereupon began a systematic search for a synthetic hormone with the maximum growth-retarding properties. They synthesized and tested many compounds, and found that the most promising was the sodium salt of 4-chlor-2-methyl-phenoxyacetic acid. This was accordingly tested in field trials in many parts of the country, with striking success. The substance is marketed under the proprietary name of Methoxone.

XII

THE BORDERLAND OF CHEMISTRY

COLLOIDS

THE word *colloid* from *colla*, meaning glue, was given by Graham in 1861 to substances like glue, gelatin, and gum-arabic, which diffused with exceptional slowness through water. On the other hand, substances like common salt, which spread through water with great rapidity, he called crystalloids, because they were invariably bodies which could easily be obtained in a crystalline form. His apparatus, shown in Fig. 63, consisted of a sheet of parchment stretched over a ring of wood, or other material to form a shallow dish or basin. This was floated on pure water contained in a larger vessel, and the solution under examination was poured into the dish with a parchment bottom. While crystalloids readily passed through the membrane into the outer vessel, colloids refused to do so, and Graham concluded that either the molecules of colloids were larger than those of crystalloids—which is certainly true in some cases, or the 'molecule' of a colloid consisted really of a group of molecules.

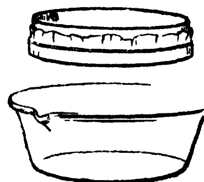


Figure 63. Graham's dialyser

In the course of his work he succeeded in preparing what seemed to be solutions of such bodies as silicic acid and ferric hydroxide, which in the dry state are insoluble in water. These preparations, however, were perfectly clear and transparent, and they passed through filter paper just as common salt does when in solution; yet the apparently dissolved substance was retained by the parchment. He called them colloidal solutions, or 'sols'. Examples of such solutions had been known before his time, but he was the first to make a full and exhaustive inquiry into the phenomena. Thus, Faraday in 1857 had prepared a clear red liquid by adding a few drops of a solution of phosphorus in ether to a dilute solution of gold chloride. Ordinarily any reducing-agent added to a solution of gold chloride would have precipitated the gold as a brown

powder, soluble only in 'aqua regia', a mixture of nitric and hydrochloric acids. But in this liquid no particles could be seen, nor were any deposited on standing. Nevertheless Faraday believed that the solid particles of gold were there, though so small as to be invisible even under the microscope.

A few years later, to be precise, in 1869, Tyndall was studying the effect of fine particles of dust, etc., in air and other gases; and, for the purpose of detecting particles which were beyond the range of microscopic vision, he passed a powerful beam of light through the containing vessel. When this was viewed at right angles to the general direction of the light, which was screened from the eye, a visible beam revealed the presence of solid or liquid particles by the scattering of light from their surfaces. While this method is still used, it has been replaced by a much more effective instrument, which is based on the same principle. The

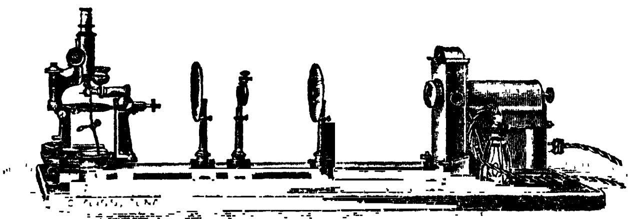


Figure 64. The ultra-microscope

ultra-microscope, as it is called, was invented by Zsigmondy and Siedentopf in 1905. It consists (Fig. 64) of a microscope mounted vertically and having on the stage a small glass or quartz trough in which the liquid under examination can be placed. The liquid is illuminated by a narrow slit in a small screen upon which are concentrated rays from the sun or a powerful electric arc. With this arrangement no light can enter the objective of the microscope unless it is reflected from solid or liquid particles in the trough. If these are present, the observer sees, not the soft glow that characterizes the Tyndall beam, but flashing points of light like moving stars in a velvet sky. About this movement something will be said presently.

The invention of the ultra-microscope gave a great impetus to the study of colloids, and by this and other methods it is clear that their properties arise from the fact that they are composed of particles varying from microscopic dimensions down to single molecules. The diameter of the smallest object visible in an ordinary microscope is $\frac{1}{100,000}$ of an inch; that of the smallest particle in the ultra-microscope is about $\frac{1}{25,000,000}$ of an inch; the diameter of a molecule of hydrogen is

$\frac{1}{250,000,000}$ of an inch. Yet a molecule of hydrogen would probably be seen if only a sufficient amount of light could be concentrated upon it. It follows, however, that a cube composed of 27 molecules of hydrogen or a square slab of 9 molecules could be seen if it were suspended in a medium from which it differed sufficiently in refractive index, so that the light which fell upon it were reflected at its surface.

Colloids owe their special properties—properties which distinguish them from matter in the solid, liquid, and gaseous conditions, to the special range of size of their particles. Suppose a cube of one inch edge be divided into eight equal cubes. The area of a surface of the inch cube will be six square inches, of one of the small cubes $1\frac{1}{2}$ sq. in., and of all the eight small cubes 12 sq. in. Next, suppose that each of the smaller cubes is further subdivided into eight equal cubes. The surface of one of the smaller cubes will be $\frac{3}{8}$ sq. in., and as there will be 64 of them, the total surfaces will be 24 sq. in. Finally, suppose that the process be repeated with each of the small cubes. The edges now will be $\frac{1}{8}$ in., the surface of one of them $\frac{3}{32}$ in., and the total surface 48 sq. in. It will be obvious that by subdivision the surface of each particle decreases less rapidly than the volume or weight, and that, if the inch cube weighed one ounce, the surface of the same weight of material will have increased from 6 sq. in. to 48 sq. in. Meantime each particle will have only $\frac{1}{512}$ volume and therefore will weigh only $\frac{1}{512}$ of an ounce.

Two consequences follow from this enormous extension of surface for the same weight of material. A particle of such a size that the ratio of surface to weight is large, sinks very slowly in a liquid or gas because the friction is relatively high. Even visible particles of small size remain suspended for a long time, as anyone will have observed who has travelled along dusty roads in summer, watched the smoke from a pipe or a chimney, or shaken up very fine mud in a cylinder of water. The effect of friction, therefore, upon colloidal particles must be very much more pronounced. But it is not sufficient to account for the stability of sols, and there must be some additional reason why the particles do not settle in accordance with the law of gravitation.

The explanation has been found in a half-forgotten discovery of Robert Brown, a botanist, in 1827. He observed that fine particles of non-living matter of the most varied description suspended in water were in a state of rapid motion. The experiments were repeated by other workers at intervals and several theories were proposed. Fig. 65 shows the movements of a particle as mapped by Victor Henry. As early as 1863 Wiener, and later others, suggested that it was due to the bombardment by the molecules of the liquid which, according to the kinetic theory of matter, are themselves in rapid motion. This theory asserts that the particles of all bodies are in motion—most violently in a gas,

less violently in liquids, still less vigorously in solids, but at rest only at the absolute zero of temperature, to which reference has been made in Chapter X.

The second consequence of extended surfaces is that a number of chemical reactions may occur which do not obey the ordinary laws which govern chemical changes. Thus freshly ignited charcoal, which is a porous material and thus has a large surface, will take up 170 times its own (apparent) volume of ammonia at 0° C. and under normal

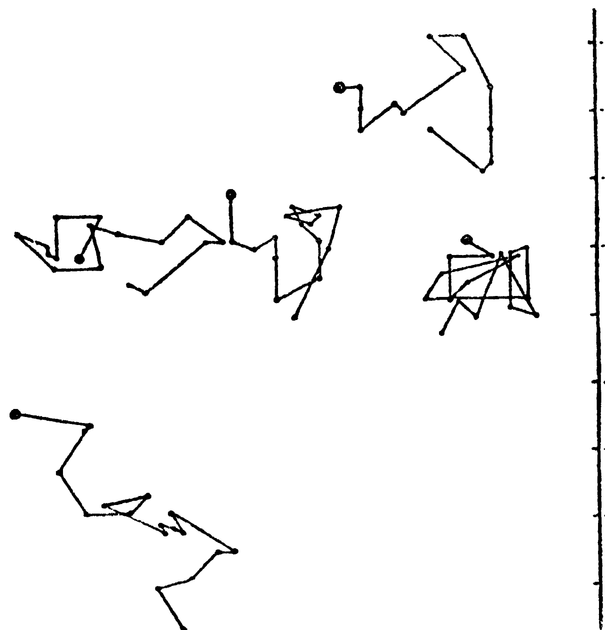


Figure 65. Diagram showing the successive positions of a single particle at intervals of $\frac{1}{20}$th of a second

pressure. Other gases, such as ethylene, carbon dioxide, carbon monoxide, oxygen, and nitrogen, are also taken up, but in smaller quantities. In all cases the quantities are greater at low than at high temperature.

Charcoal—more especially animal charcoal—also takes up colouring matter, quinine sulphate and lead salts from solutions, and is used to remove the brown colouring matter from syrup in the manufacture of sugar, and fusel oil in the manufacture of whisky. Filter paper, which is also a porous substance, abstracts lead salts from solution, and china clay and fuller's earth are used for purposes similar to that in which charcoal is employed. The hydroxide of aluminium and similar sub-

stances take up the colouring matter from the solution of a dye and form substances called 'lakes'.

There are obviously two methods of preparing small aggregates. One is to disintegrate a mass, and particles of colloidal dimensions are actually produced by grinding. Another is to build up the aggregate from individual molecules. As an example of the first method sols of metals can be most easily obtained by forming an electric arc between two rods of the metal immersed in the liquid in which the colloid is to be suspended. A simple method of preparing hydrosols (colloidal solutions in water) of gums and similar substances is to add a few drops of a solution of the gum in alcohol to about 100 c.c. of water. A milky fluid is obtained from which the particles do not settle and from which they cannot be removed by filtration through ordinary filter paper. And as an example of the opposite process, any chemical reaction which produces an insoluble substance may, if performed with dilute solutions, produce a sol. The molecules of the insoluble substance are formed singly and are so few and so distributed that the aggregates formed are ultra-microscopic in size.

Many substances like gelatin, glue, etc., set to a jelly on standing, while silicic acid also forms a jelly by loss of water or the addition of an electrolyte. In this condition they are called gels to distinguish them from sols. As a rule they can be redissolved to form the sol. The gels are an extraordinarily interesting class of substances. Gelatin, and some of the gums for example, absorb water and swell, and as the volume of swollen substance is less than that of the original gel plus the water, contraction must occur, and enormous forces brought into play. They appear to possess a definite structure like a sponge and to differ from sols in which a solid is dispersed in a liquid in that the liquid phase is distributed throughout a solid or semi-solid framework. In gelatin gel the framework is elastic, in silicic acid gel the framework is rigid.

Sols in which a solid is dispersed in a liquid are called suspensoids, but there are a large number of cases in which both the dispersed substance and the medium are liquids. These are called emulsoids. Oil, soap, and many other liquids may be dispersed in water and, *vice versa*, water may be dispersed in many other liquids. Perhaps the commonest example of an emulsoid is milk, which contains globules of fat dispersed throughout the butter-milk—the butter-milk also containing two colloids called casein and albumin.

Primarily milk is a colloidal solution or an emulsoid of fat in water, the fat amounting to 3·6 per cent. By churning milk or cream, the fat globules are collected, and the resulting butter is a solid emulsion of water in fat, containing 84 per cent fat and 13 per cent water.

Milk also serves to illustrate another remarkable fact. Certain substances are only stable in the colloid condition when another colloid

is present. The latter is called a 'protecting' colloid. In milk the albumin acts as a protecting colloid to the casein, and when the albumin is destroyed by rennet or by acids (sour milk contains lactic acid produced by the action of bacteria) the casein is precipitated and the milk is said to curdle. This has an important bearing on digestion. Asses' milk for example contains about three times the amount of albumin and only about one-fifth of the amount of casein in cows' milk, and can be digested by infants far more easily. The 'protection' of the casein particles in asses' milk is more complete and curd is not only less readily formed, but when formed is in smaller flakes.

One of the most interesting cases of protective colloid is afforded by ice-cream. If this is made without eggs, gelatin, gum-tragacanth or similar colloid (generally called a 'filler' in the trade) it is, or soon becomes, gritty or sandy in texture; but if one of these 'protectors' is present a smooth, velvety texture is secured and retained. It is interesting to note that the added colloid serves also to prevent aggregation of the small crystals of ice which are present and which in time would tend to coalesce. Of the substances mentioned, gelatin is far the most effective and half of one per cent is sufficient to achieve the purpose. The ice-cream maker is probably more familiar with the facts than the explanation.

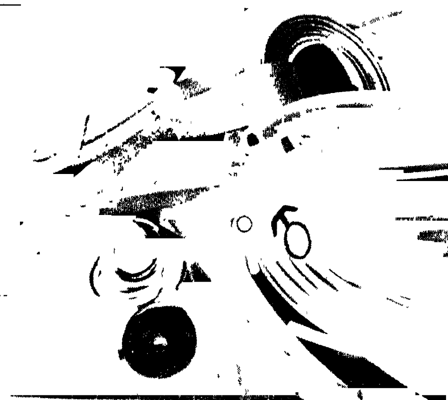
The separation of the fat globules from milk to form cream can be prevented by 'homogenizing' the milk. This process consists in forcing milk at a temperature of 50°–60° C. through very fine orifices under considerable pressure, which causes a reduction of the fat globules to one-hundredth of their original size. Such milk cannot be churned for reasons which would take us too far afield. It is also possible to homogenize cream which cannot then be churned, nor, again for reasons which must again be omitted, can it even be 'whipped' unless a colloid such as gum-tragacanth is added.

Perhaps the most familiar of all colloidal substances are soaps, which are the sodium or potassium salts of oleic, palmitic, or stearic acids. The sodium salts are hard soaps, the potassium salts are soft soaps. If calcium or magnesium be substituted for sodium or potassium the resulting soap is insoluble. That explains the curd produced when ordinary soap is used in hard water. The soluble soaps form colloidal solutions with water, and owe their detergent properties to this fact.

One of the most important industries which finds an explanation of its processes in the properties of colloids is Tanning. Skin, after the hair and epidermis have been removed, is composed of *collagen*, a near relative of gelatin, and its texture is a net-work of fibres which are really colloidal jelly. When the hide is dried the fibres cling together, forming a horny mass. The process of tanning consists in separating the fibres so that the leather may be flexible and porous, and so treating them as



XXIXa. An operator watching the growth of synthetic sapphires at the G.E.C. Laboratories



(I.C.I.)



(I.C.I.)

XXIXb. Extruded sections of polythene

XXIXc. Alkathene tubular film



XXX. Results of continuous wheat-growing experiments at Rothamsted for 56 years

to render this condition permanent. The former is effected by soaking in dilute acids or alkalis and the latter by adding substances which alter the chemical character of the fibres or cover them with a protecting coating. The latter is a mineral substance such as chromium hydroxide, a vegetable substance such as tannin (both of these are colloids) or an oil (which may be a colloid).

The artificial silk and synthetic fibres industry, which has had such a meteoric development in recent years, again uses colloidal material. Real silk is an exudation of the silkworm, and consists of the cellulose originally contained in the leaves upon which the worm feeds. Woody fibre of all plants is composed mainly of this substance. Mashed up and mixed with a little size, spread out in a thin layer and dried between hot rollers it forms paper. In the stem of the flax plant and the boll of the cotton plant it is found already in the form of fibres which can be spun and woven into linen or cotton cloth. The difference between woody fibre, linen, cotton, and silk is almost entirely one of structure. All of them are composed of cellulose, and cellulose is, or rather behaves like, a colloidal substance.

Hooke, in 1665, was the first to suggest that silk might be formed artificially by solution of a gum. In 1855 a Frenchman named Andomars made cellulose nitrate by treating it with nitric and sulphuric acids, and dissolved this in a mixture of alcohol and ether. If this was forced through a fine orifice the alcohol and ether evaporated, leaving a fine thread of cellulose nitrate which could be reconverted into cellulose without appreciable alteration of form. The technical experience necessary to develop this process was not available at the time, and it was left to Count Hilaire de Chardonnet to work out the process on a commercial scale.

A cheaper process is that in which the cellulose is dissolved in an ammoniacal solution of cupric hydroxide. Cotton fibre is, however, used in this process in place of wood pulp. Another method is to use cellulose acetate, and the fibre so produced is called celanese.

In the viscose process, cellulose zanthate is formed by treating cellulose with carbon disulphide. Cellulose zanthate was first made by Cross, Bevan, and Beadle in 1892, and it is the application of this discovery more than anything else which has led to the enormous expansion of the industry.

It will be observed that in all these processes the cellulose, in the form of wood pulp, or cotton, is first converted into a compound soluble in a particular solvent. It forms a more or less viscous or gummy solution which then is forced through a fine orifice, or a number of fine orifices in a nozzle. If the solvent is volatile like the ether-alcohol mixture or acetone, the filament may be dried in air. With non-volatile solvents the filaments pass into a bath filled with a substance that

abstracts the solvent. For cellulose nitrate both dry and wet methods are used. The filaments are so fine that a number of them have to be wound together to form a yarn sufficiently strong for wearing.

The discovery of the Chinese perhaps 5,000 years ago that the cocoon of the silk worm could be used for making beautifully light, soft, and warm garments for human wear is a wonderful example of observation, patience, and ingenuity. But the material was always so rare that only the wealthy could afford it. Indeed, silken garments were among the privileges of Paradise that Mahomet promised to his followers. Yet the development of chemical science during the last hundred and fifty years has enabled man to produce a desirable alternative, at a price within the reach of many people.

SYNTHETIC PLASTICS

Materials of natural origin, such as horn, ivory and tortoise shell have always interested the human race as materials for the fabrication of certain articles. These are the primitive plastic materials, and were worked thousands of years ago in a way similar to that now used for the most modern of plastics. The vegetable kingdom as well as the animal, depends on materials closely allied to what are now called plastics, for their structural materials. This is perhaps best illustrated by cellulose in plants.

The early industrial chemist sought to reproduce the natural materials largely as a result of shortages, and the synthetic plastics industry grew through an attempt at manufacturing synthetic ivory, tortoise shell, horn and amber. During the past twenty years, however, the point of view has changed. The chemist is no longer concerned so much with trying to imitate Nature, but to produce by his own processes, whether they occur in Nature or not, materials which have properties demanded by the newer industries, or are adaptable to modern methods of mass production.

The early chemists kept close to natural materials and some of their discoveries were at least partly fortuitous. Of recent years the general configuration relating to the structure and properties of polymeric substances has been gradually worked out by research, and as a consequence there exists a certain ability to fabricate plastic materials, having the general properties desired, on a basis of purely theoretical considerations.

The plastics owe their most characteristic properties to their being made up of long-chain molecules. The single molecules of their basic material are bound together in chains by primary valency forces between them. Then the chains are held together in bundles by weaker secondary forces.

The individual molecules of the basic material are made to form chains by two processes, polycondensation and polymerization. In the first of these processes the molecules are made to join together through the elimination of water. Nylon is made in this way.

In the second process, molecules containing double chemical bonds are brought into a chemical environment which enables them to link up together.

The lengths of the chains in these synthetic materials are never all the same. They vary around an average. The variation and distribution around the average can be modified by treatment during manufacture. This may confer on the product a variety of mechanical properties, and allow the production of a range of materials suitable for a variety of uses.

The chains can perform many kinds of movement, under different conditions of temperature. They may curl or uncurl, and if they can do this quickly they may have rubber-like properties. Owing to the tendency of their long chains to movement, the properties of many plastics depend on time. A plastic which is flexible when stretched slowly may become brittle when stretched quickly. Much has yet to be learned about the principle of plastic flow, and a great deal remains to be learned about the behaviour of plastics over long periods of time.

If the chains are mainly similar in shape, they may pack together with a regular structure, and exhibit crystalline properties. The strength of nylon is related to the strong forces of the hydrogen bonds which hold its chains together. Its flexibility is connected with the ability of its chains to pack together closely, and crystallize. When the nylon is stretched the chains in these crystallites acquire a still more precise order, increasing their strength as a basis of fibres. The crystalline structure does not break down until a temperature of 264° C. is reached.

Nylon is the name given to the polyamides first synthesized by W. H. Carothers in America in 1929. The starting-point is benzene or phenol, derived from coal. The benzene C_6H_6 is converted into cyclohexanol $C_6N_{11}OH$. From this is derived adipic acid $HOOC(CH_2)_4COOH$, and thence adipontrile $NC(CH_2)_4CN$. From the latter, hexamethylene diamine is derived, $H_2N(CH_2)_6NH_2$. Adipic acid and hexamethylene diamine are condensed to form nylon salt. Nylon is derived from this by polycondensation.

One of the most interesting plastics developed in England is polythene. This is derived from the simple gas ethylene, CH_2:CH_2. Its discovery and development are due to fundamental research and collaboration between Professor A. M. J. F. Michels of Amsterdam, and the Imperial Chemical Industries. Professor Michels belongs to the famous Dutch school of physicists devoted to the study of the properties of gases. He was concerned with more accurate measurements of the

relation between volume and pressure in gases, and for this purpose developed the technique of experimenting with gases at very high pressures. His laboratory, which is surprisingly small and neat, is a brilliant example of ingenuity and rationalization in research. He evolved methods by which exact experiments at very high pressures could be made quickly and comparatively easily, and with this technique laid open a whole new field of research on the properties of gases at very high pressures.

The Imperial Chemical Industries began to collaborate with him soon after the First World War, and this was followed by mutual exchanges of staff.

It was natural to expect that very high pressures might cause the molecules in some gases to link together in chains, and Michels found experimental evidence that suggested that this might occur in ethylene. Imperial Chemical Industries decided to undertake systematic research on the effects of very high pressures of 15,000 to 300,000 lb. to the square inch on chemical reactions, in 1930. A laboratory was established in 1931, and research on chemical reactions under very high pressures began in 1932. Little was found at first, but in 1933 a trace of a white solid was noticed in a reaction vessel in which ethylene had been submitted to a very high pressure. This proved to be a solid polymer of ethylene.

Very high pressures produce a range of solid ethylene polymers, and these have been given the general name of polythene.

After the original discovery of the first polythene, two years passed in developing the technique, and building bigger apparatus to produce more of the material. Such pressures had never before been regularly used in an industrial process. The apparatus often exploded, and on one occasion, the laboratory was badly damaged.

Unremitting research showed that the process could be safely controlled if the ethylene gas was sufficiently pure. By 1936, a continuous process, which promised to operate satisfactorily at the novel ultra-high pressures, had been worked out. This was essential if the process were to become industrially practicable.

It was necessary to devise new kinds of gas compressors, joints, valves, tubing and reaction vessels which would work at the tremendous pressures, which are of the same order as those in gun explosions. The solution was found by adapting the technique used in artillery manufacture to the new chemical process.

A pilot plant capable of demonstrating a full-scale manufacturing process for polythene was completed in 1938. Meanwhile, the properties of polythene were thoroughly investigated from the small quantities which were being produced in the laboratory.

It was soon found that polythene had remarkable properties as an

insulator. It was very tough, flexible, light and resistant to water. Submarine cable manufacturers were at once interested, and a mile length of experimental submarine cable insulated with polythene was made in 1939.

The properties of polythene for insulating very high-frequency electrical equipment, such as is used in radar and television are even more remarkable than its value in submarine and ordinary telephone and telegraph cables.

Imperial Chemical Industries decided to establish a full-scale manufacturing unit. This started production on 1st September 1939, the very day on which Germany invaded Poland. The first ton of polythene from the new unit was assigned to experimental work with radar. In the early months of 1940, most of the output was, however, being used in special submarine cables. But when the second manufacturing unit came into operation at about the time of the Dunkirk evacuation, the bulk of the output was already being devoted to radar equipment. Sir Robert Watson-Watt said that polythene 'transformed the problems presented by airborne radar from the almost insoluble to the comfortably manageable', and 'played an indispensable part in the long series of victories in the air, on the sea and on the land, which were made possible by radar'.

The use of polythene in radar cables was of outstanding importance, but it had many other applications. It was found that the anti-malarial drug mepacrine was best protected from deterioration in hot damp tropical climates by packing in sheets of polythene. Under these conditions it remained good, even when the package was immersed in water.

The polythene chain contains five hundred or more ethylene molecules. These are linked together under extreme pressure and temperature with the aid of a catalyst. The ethylene is secured from alcohol prepared from molasses by catalytic dehydration, or from the gases obtained by cracking petroleum. The ethylene is very carefully purified, and mixed with a slight but precisely determined amount of oxygen. The mixture is compressed in two stages to 16,800 lb. per sq. in. and delivered into a reaction vessel at 200° C. A considerable amount of heat is produced by the linking of the ethylene molecules. The polymer emerges as a clear liquid, and is cast into blocks.

The I.C.I. brand of polythene: Alkathene, is a tough, waxy-looking substance. It is normally white, but sometimes pink or grey. It is made in the form of sheets, rods, and granules or chips.

Besides its remarkable dielectric strength and other physical properties, it is very resistant to acids and alkalis. It is thermoplastic, i.e. it can be moulded by heat, and can be extruded. It begins to yield at about 90° C. and melts at 115° C.

Alkathene sheet has an attractive translucent white appearance, and

can easily be coloured with pigments. An interesting new application is as a material for stratosphere balloons. Professor C. F. Powell has adopted it in the balloons he uses to take cosmic-ray recording equipment up to heights of 100,000 ft. The sheets of Alkathene are easily joined by a slight application of heat.

Another application is in pipes for cold-water plumbing and drainage. These can be laid by special ploughs. Waterpipes made of Alkathene do not burst when frozen. They are being adopted, too, in beer-pumping installations in bars and breweries. Small sheets are used for wrapping parcels, and big sheets for protecting motor-cars from the weather (Plate XXIX*b*).

A NEW FIBRE

An interesting new synthetic fibre was discovered by J. R. Whinfield and J. T. Dickson of the Calico Printers' Association, about the year 1940. It has been named Terylene, and its manufacture on a large scale is being undertaken by Imperial Chemical Industries.

The fibre is made by polycondensation from polyethylene terephthalate, which is a condensation product of terephthalic acid and ethylene glycol. Both are derived by chemical synthesis from the products obtained by cracking petroleum.

As Terylene was discovered during the Second World War, the patents covering it were declared an official secret. The first yarn was made from Terylene fibre in 1944, and showed promising qualities. In 1947, the Imperial Chemical Industries acquired the world-rights to develop the new fibre.

Pilot plants for making the polymer, and for spinning the yarn were ready in 1949. The spinning plant produces at a rate of about 600,000 lb. of yarn and fibre a year.

The experience gained with the new fibre opened wide prospects of development, and in 1950, I.C.I. launched a project for its manufacture on a large scale. An initial expenditure of more than £10,000,000 has been allotted for the construction of plant to make the raw material, p-xylene, and large factories for making the polymer, and for spinning it. These plants are being erected at Wilton in North Yorkshire, near to the I.C.I. petroleum cracking plant. They are expected to be in operation in 1955, with an annual output of 11,000,000 lb. of fibre, and will give employment for about 1,000 men. They are part of a wider scheme of development at Wilton, the first two stages of which are to be completed in that year, at a cost of £39,000,000.

Terylene is as strong as nylon, and unlike nylon, its strength does not decrease when it is wet. It absorbs little moisture, is easily washed, and quickly dries. It does not require ironing. Its modulus of elasticity is

about four times that of nylon, which is an advantage in weaving or knitting. Its specific gravity, or weight, is considerably more than that of nylon: 1·38 to 1·14.

Terylene is several times more resistant to abrasion or wear than viscose or acetate rayon, but it does not approach nylon, which is 2 to 4 times more resistant than Terylene. The extremely high resistance of nylon to abrasion helps to explain its wearing quality in stockings.

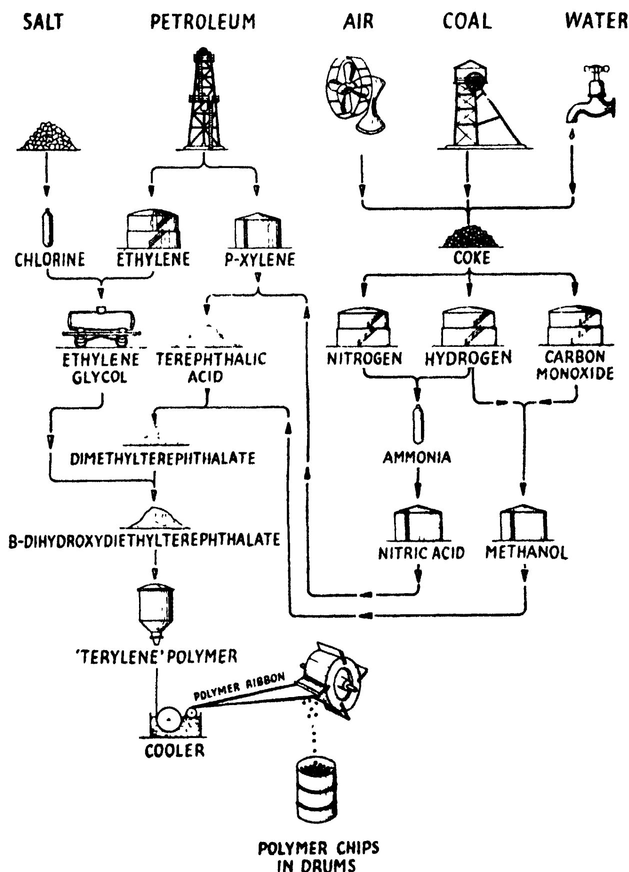


Figure 66. How a terylene polymer is made

Terylene is much more resistant to heat than nylon and other fibres, and to change of colour. It is not attacked by moths, white ants, silver fish, fungi or bacteria. It has a warm handle, and good resistance to creasing.

Terylene is spun by a process similar to that worked out for nylon.

The polymer is fed in the form of chips into a melter. The hot liquid is then pumped through a spinneret at a carefully regulated rate. The filaments formed in this way solidify very quickly, and can then be drawn off, and wound into yarn. Very high spinning rates can be achieved, which partly compensates for the high cost of the equipment.

Terylene filament yarn makes materials like those of silk or nylon.

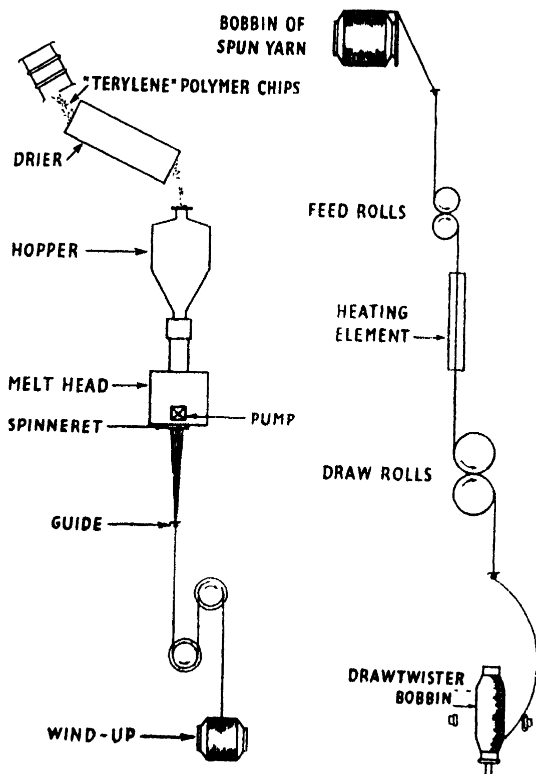


Figure 67. How a terylene continuous filament yarn is made

Terylene staple fibre has been made to have a more wool-like character, to be handled by worsted processes.

The first uses for Terylene will be for socks, underwear, lingerie, shirts and curtains. Voiles, taffetas, poults, satins, brocades, velvets and warp-knitted fabrics of Terylene are being developed. Knitted warm underwear, pullovers, etc. will be produced.

As Terylene staple fibre is resilient, it makes a lively and springy cloth. Skirts and trousers made from it will resist bagginess. The springiness helps Terylene socks to remain comfortable. Creases can be put

in Terylene with a hot iron. These remain, even after domestic washing, but can easily be ironed out again.

Besides its use as a domestic textile, Terylene has many industrial applications. Filter cloths made of it last at least five times as long as those made from wool or cotton cloth. It is utilized as an insulator, and as a rope for hawsers, fishing lines, etc. Terylene thread is used for sewing, where great strength, resistance to acid (Terylene is remarkably resistant to hydrofluoric acid), and sunlight are needed.

THE UTILITY OF FROTH

The froth formed by stirring up or blowing air through water lasts only for a short time, but if certain substances are present, such as soap, oil, etc., the froth is much more permanent. Colloids are especially effective both in promoting the formation of froth and in conferring lasting properties upon it.

The surface tension of a liquid is profoundly modified in contact with a solid, and the influence is manifested by the different degrees to which different liquids will 'wet' the surface of a particular solid. From these two facts—the formation of froth and the 'wetting' of solid surfaces—have arisen one of the most important groups of industrial operations.

Many ores of metals occur in narrow veins from which they cannot be removed free from rock and they require to be 'concentrated' before smelting is possible. The usual method of carrying this out has depended upon the fact that the ore has a higher specific gravity than the gangue with which it is associated. The material from the mine, therefore, was crushed and subjected to the action of running water, which washed the lighter particles of rock away while the particles of ore sank to the bottom. But the separation was never very complete. The particles varied in size and the lighter ore particles were washed away with most of the gangue while some of the latter remained behind. It was rarely possible to recover more than about 80 per cent of the ore contained originally in the material.

The colloidal process takes advantage of the facts (*a*) that a froth can be produced in water containing the crushed ore, (*b*) that this froth can be rendered permanent by the addition of a very small quantity of an oil or mixture of oils, (*c*) that the oil wets the particles of ore more readily than it wets the particles of gangue, and (*d*) that the oil all goes into the froth. Consequently when a mixture of crushed ore is stirred up with, say, ten times its weight of water containing a small quantity of oil as stabilizer, the ore becomes attached to the air bubbles which are formed and rises up into the froth, while the lighter gangue sinks to the bottom of the water. The separation is more complete if

a small quantity of acid, say, sulphuric acid, is added, for this wets the surface of the gangue more effectively than water, so both oil and acid are used. The process takes less room than the older one, is quicker in action, and far more efficient. It has come into widespread use for the treatment of copper, zinc, and lead ores. At Anaconda, the percentage of ore extracted is 95 compared with 76 under the old system, and in other places ores which formerly would hardly pay to concentrate are rendered profitable.

The process was first worked out for sulphide ores. It could not be applied without modification to other compounds in which metals occur because the relation between the oil-water surface, the ore and the gangue are not necessarily the same. But materials have been found which enable the cassiterite of the Cornish Tin Mines to be separated from its gangue.

A very important extension of the process has been made to the separation of fine coal from the dirt with which it is invariably accompanied. The coal is crushed and sifted through a mesh with not fewer than ten holes to the inch, and delivered into about four times its weight of water in the vertical chamber. To the water is added cresol and paraffin oil in the proportion of one pound of the mixture to a ton of coal. The whole mass is then violently stirred, a black froth containing practically the whole of the coal is produced and can be run off from the outer vessel into the upper dish and the dirt is run off from the bottom into the lower dish. By this means the amount of dirt in the coal can be reduced to one-quarter of that contained in the original coal.

Whipped cream over a dish of fruit confers upon it an additional attraction, and the 'head' on a glass of beer is accepted as evidence of condition. At the seaside the white-capped waves convey to our minds something of the endless succession of events, of the unchangeable onward movement of time from far back in the beginning to the distant future into which no one can see. But who, dwelling upon these phenomena years ago, could have imagined the unseen forces of the bubble being utilized to control the separation of hundreds of thousands of tons of coal and ore a year?

CATALYSIS

Many chemical changes take place at a lower temperature or more readily in the presence of a substance which apparently undergoes no alteration in composition itself.

Berzelius, in 1835, was the first to draw attention to these phenomena and to apply the term catalysis to them, and Faraday was the first to draw attention to the importance of surface. The more spongy and

porous the material the more effective it was in promoting the change. Thus, if a piece of asbestos is soaked in a solution of platinic chloride and then heated the platinic salt decomposes and platinum in a finely divided condition is left on the fibres. The 'spongy platinum' thus formed is more effective than a sheet of the metal. This suggests that 'adsorption', which has already been described is the primary cause, though until we know more about adsorption it does not carry us very far. Still, wherever a solid catalyser is used its value depends largely upon its extended surface, and ingenious ways of 'mounting' the fine particles have been devised. In some cases brick is soaked with a solution and dried; in other cases asbestos is employed.

It will be obvious that the possibility of speeding-up a process or of carrying it out at a lower temperature is of enormous importance from an industrial point of view. But the transfer of a process from the laboratory to the works is attended with two difficulties. In the first place the rare metals, platinum and palladium, which were found to be so effective in the earlier experiments are too expensive to be used in large quantities, and extensive researches have had to be undertaken to discover cheaper materials. Nickel, copper, iron, and many metallic oxides have been used, and in some cases a second substance has been found to increase the activity of the catalyst itself—such a substance is called a 'promoter'.

The second difficulty in commercial applications arises from the fact that an impurity in the reacting substances rapidly reduces the effect of the catalyst or 'poisons' it. Though this fact had been discovered in the laboratory it became of far greater importance when working with large quantities on a commercial scale because of the difficulty and expense of securing pure materials; and applications to industry have been delayed until this part of the problem could be solved.

Thus sulphuric acid has been manufactured by the chamber process since about 1750 and every text-book of chemistry contains an account of it. The space occupied by the plant is very large; the capacity of a single set of three chambers may be 150,000 cubic feet. The direct union of sulphur dioxide, SO_2, and oxygen under the influence of platinum to form sulphur trioxide SO_3, was suggested by Davy in 1812 and attempted by Phillip in 1831; but success was not attained until 1901 and development has been very rapid since then.

In the contact process, as it is called, the sulphur dioxide and air from the pyrites burners have to be thoroughly freed from dust, finely divided sulphur, arsenic, antimony, and lead by washing and cooling. They are then led in through a 'converter' containing the catalyst, care being taken to secure a temperature between 400° C. and 450°. As catalyst burnt pyrites (CuO,Fe_2O_3) has been used for the preliminary conversion but the final product is always obtained by the aid of

platinum. In the Schroder-Grille process, the heated magnesium sulphate may contain only 0·2 per cent to 0·3 per cent of platinum, but is so active that 5 grains of platinum enable a ton of acid to be produced a day. The gases are absorbed in sulphuric acid, which is more effective than water.

The acid obtained by the contact process is called oleum on account of its appearance. It is stronger than the ordinary acid, having the composition $H_2S_2O_7$—like the old Nordhausen sulphuric which used to be prepared by heating crystals of green vitriol $FeSO_47H_2O$. It is essential for certain chemical processes for which the ordinary acid is less suitable. The ordinary acid can readily be obtained from it by the addition of water. The production of sulphuric acid in Britain in 1951 was 1,606,078 tons of 100 per cent acid, i.e. the weight of pure H_2SO_4 in all the acid produced.

Hydrogen gas is usually prepared in the laboratory by dissolving zinc or iron in an acid, but this method is too expensive when large quantities are required for industrial purposes. Another plan which is employed is to pass steam over red-hot iron. A still more recent plan involves the aid of a catalytic agent. Thus, as explained in Chapter II, if steam is passed over red-hot coke in a converter (Fig. 14) a mixture of carbon monoxide and hydrogen is produced. If this mixture, together with steam, is passed over finely divided nickel, cobalt, tin, or oxides, or a mixture at a temperature of 400° C. to 600° C. under a pressure of 4 to 40 atmospheres (60 lb. to 600 lb. per sq. in.) the following reaction takes place:



$$CO + H_2O + H_2 = CO_2 + 2H_2.$$

The CO_2 is absorbed by passing the gases, still under pressure, through water or milk of lime. It is interesting to note that a third of the energy used for driving the pump is recovered by causing the liquid in the adsorption vessel to drive a Pelton Wheel. The process is continuous and once it has started the temperature is maintained by the heat produced by the reaction. Moreover, the hydrogen is of a high degree of purity and extremely suitable for use in the next process to be described.

Animal and vegetable oils have been used for centuries for making soap, and especially within the last fifty years for making margarine. They consist of an organic acid combined with glycerine, and displacement of the glycerine by soda or potash results in a soap. But the growth of the margarine industry made great inroads upon the raw material of the soap manufacturer, who began to look round for other materials. One well-known soap manufacturer complained that he no sooner obtained a new fat for soap making than the manufacturer of margarine also began to use it. Finding olein and stearin from beef fat becoming expensive he began to use cocoanut oil or palmitin and other natural oils or fats.

Now these natural products occur in two parallel series. In each series the molecules of the successive members differ by one atom of carbon and two atoms of hydrogen—in other words by the group—CH_2. The series differ from one another by two atoms of hydrogen. That is to say, in one series each member has two atoms of hydrogen less in the molecule than the corresponding member in the other series.

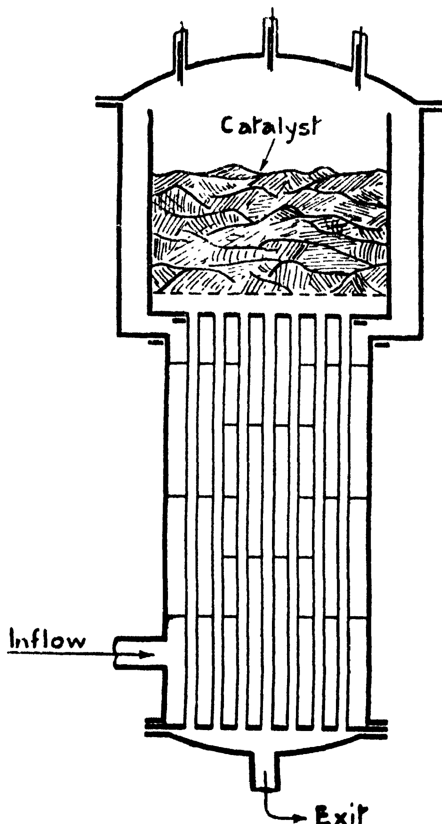


Figure 68. Diagram of catalytic process for the manufacture of hydrogen

Comparing the lower members of each series, the substances which are short of hydrogen are liquids, and those which have their full complement of hydrogen are solids, or semi-solids. The latter are called saturated compounds and are most useful; the former are called unsaturated and are less useful. The solid substances are used to make

candles. The possibility of hardening fats, or converting an unsaturated substance into a saturated one is therefore of great industrial importance.

The foundation was laid when Sabatier and his colleagues, particularly Senderens, showed from 1897 onwards that many unsaturated compounds would take up hydrogen in the presence of nickel and many of its compounds and become saturated. A large amount of useless material has by this process been rendered useful, and an increased consumption of necessary materials rendered possible without a corresponding increase in price. People today are eating with relish fats which fifty years ago the candle-maker could not, and the soap-maker would not, use.

To the demand of the world's crops for nitrogenous materials was added the demand of the world's armies for explosives, and the processes for manufacturing nitric acid from atmospheric nitrogen which have been described in Chapter IX were developed at a far greater rate than would have been possible in times of peace. Particularly was this the case in Germany, cut off as she was from the Chilean nitrate fields, and but for the energetic efforts of her industrial chemists, she could not have maintained her position half so effectively nor for half the time. Haber developed the direct combination of hydrogen and nitrogen under the influence of a catalyst to form ammonia.

The problem was to prepare both hydrogen and nitrogen of a sufficiently high degree of purity; to ascertain the most effective catalytic agent; and to determine the temperature and velocity of gases over the catalytic agent which give the highest yield, besides many other details. Generally speaking metals of high molecular weight which are known to combine with hydrogen or nitrogen are preferred. The temperature is 500° C. or 600° C., and the gases are circulated round and round, through the converter, the small quantity of ammonia formed each time being removed by liquefaction or solution in water, and the pressure is between 100 and 200 atmospheres—1,500 lb. to 3,000 lb. per sq. in.

The importance of the synthetic ammonia process lies in the fact that it is the most effective method of obtaining nitrogen compounds from the air. The ammonia can be oxidized to nitric oxide by mixing it with air or oxygen and passing it over a catalyst—usually platinum in the form of a fine gauze at a temperature of 600° C. to 700° C. The nitric oxide combines with oxygen in the air and water to form nitric acid. The nitrogen in the air can therefore be converted into nitric acid by two different processes—firstly, by direct union under the influence of the electric arc, and secondly by (*a*) liquefying air and separating from the oxygen, (*b*) combining with hydrogen in the presence of a catalyst to form ammonia, (*c*) oxidizing the ammonia with air, in the presence

of a catalyst. Both of these have been rendered possible by the scientific knowledge of the twentieth century. They were not possible before.

FERMENTATION

The term fermentation was first given to a number of chemical changes which were produced by the action of living things. Thus *yeast*, which is a low form of plant life, akin to the moulds, converted starch into sugar, carbon dioxide being evolved and causing the liquid to froth. Again the mould *mycoderma aceti* converts alcohol into acetic acid. These processes have been employed for many years in the manufacture of beer, stout, wines and spirits, vinegar; and many other changes occur in the presence of bacteria which are still lower forms of the vegetable world.

Changes of this kind, however, were known to occur in the presence of minute quantities of non-living substances, and under conditions in which the possibility of life was ruled out. These substances are called unorganized ferments or *enzymes*. The identity of the two processes was first indicated by Buchner, who, in 1896, squeezed out from ruptured yeast cells an enzyme called zymase, which acted in precisely the same way as the original yeast. The view today, therefore, is that the organism, animal, or vegetable, mould, yeast, or bacterium produces the enzyme, and the enzyme causes the chemical change in much the same way as the catalysts which have already been described.

Enzymes are colloids, and are extremely complex bodies which have probably never been prepared in a pure condition. Being products of a living organism they are always associated with life, and are intimately concerned in vital processes—the changes which occur in living things. They are the active directive agents by which plants build up from earth and air their structure, colour, and perfume; and in man and other animals they cause the changes which convert the food he eats into substances which can be assimilated by bone, and muscle, and nerve. Those which are obtained from animal sources are most active at a temperature of 40° C.; those from the vegetable kingdom are most effective at a temperature of 25° C.; those from cold-blooded animals exert their influence most powerfully at 15° C. At 0° C. most of them are practically inert; so that putrefaction of meat, the decay of vegetable matter and the souring of milk can be prevented or delayed by cold storage.

Their close association with vital processes is also emphasized by the fact that most enzymes are destroyed by a temperature of 60° C. and all are instantaneously 'killed' at 100° C. Hence meat will keep longer when it is cooked because the agents of putrefaction are destroyed and decay can only begin by the entry of fresh bacteria or other forms of

life which will form a fresh source of the ferments. Perhaps one reason for attributing the action to bacteria, or moulds, rather than to their product, for so long, is the fact that the action can be prevented or stopped by 'poisons'. Substances like hydrocyanic acid, sulphuretted hydrogen, mercuric chloride, iodine and many others are effective. It is upon this principle that the antiseptic treatment of wounds is based, and substances less harmful to man than those which have been mentioned are used for preserving food, e.g. borax and salicylic acid. It is possible to destroy the enzyme without killing the organism and *vice versa.*

Perhaps the commonest example of an everyday operation involving the use of an enzyme is the manufacture of cheese. A substance called 'rennet', which is produced by the glands in the mouth and stomach of animals, when added to milk causes clotting, and for this purpose one part of rennet will curdle 400,000 parts of milk. The character and flavour of the cheese depends upon the enzymes which are present. These matters are not now left to chance. Each form of lowly life produces its own particular enzyme, which attacks the material at hand in a particular way. Thus for Cheddar Cheese the Bacillus *acidi lactici* discovered by Pasteur is alone necessary, while the green mould *penicillium glaucum* is required for Gorgonzola. In order to produce the correct flavour both in butter and cheese-making, pure 'cultures' are employed, and a bitter or sour flavour or special colour are produced by organisms whose presence is not welcome.

Other applications are to be found in the curing of tobacco, and in the separation of the fibres of flax and hemp. A process that may attain very great importance is the fermentation of starch (from maize, rice, acorns, chestnuts, etc.) by enzymes from certain organisms with the production of acetone and fusel oil, the latter being a mixture of alcohols with a larger number of carbon and hydrogen atoms than ordinary alcohol.

Perhaps no more wonderful effect of the influence of enzymes can be imagined than the explanation which has been given by Dubois, McDermott, and others of the origin of light in the firefly. The body of the insect contains a substance which has been called *luciferine*, and this is oxidized under the influence of an enzyme, *luciferase*, which is secreted by the fly.

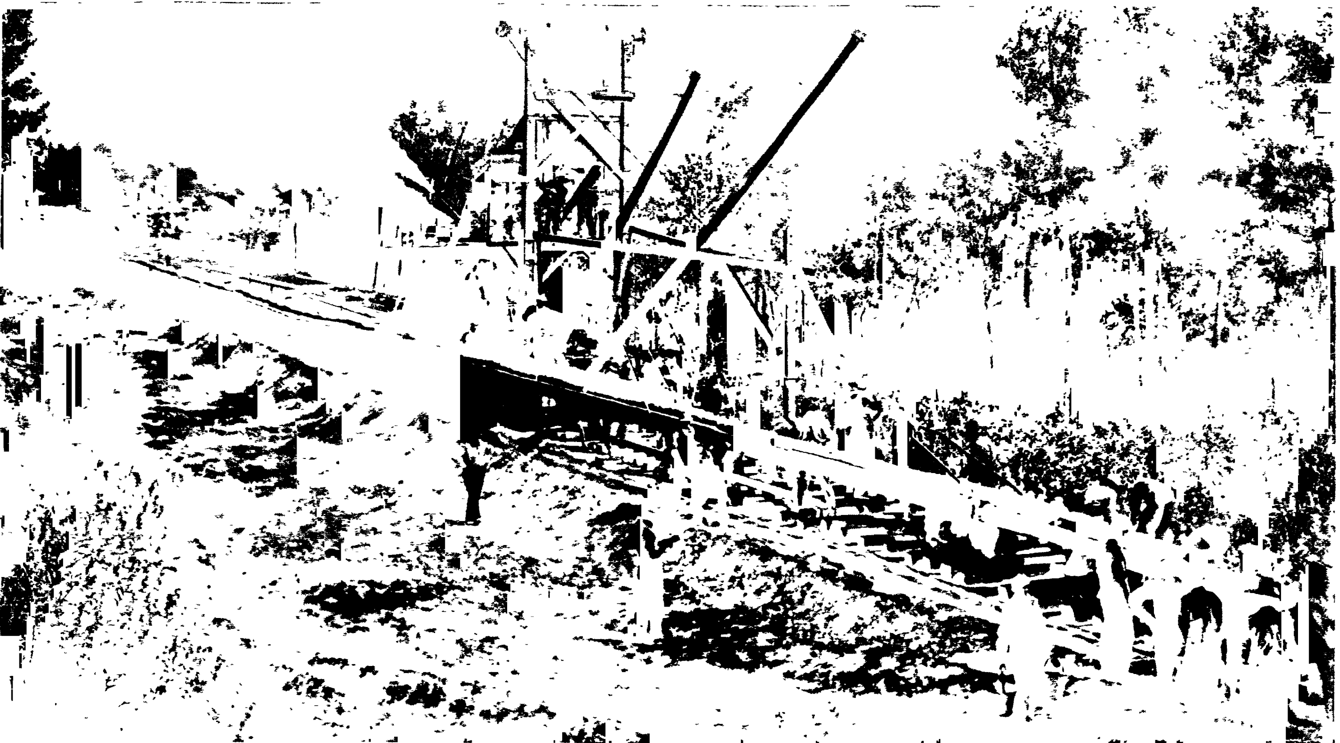
But, after all, this can hardly be more wonderful than the changes which go on in our own bodies, by which food is built up into the structures and tissues of which we are composed. This is a problem which is rapidly changing, appearing in new aspects as it is viewed in the light of modern knowledge. But it will be well to describe some of these aspects in a separate section.

From a chemical point of view, the foods of man may be grouped into four divisions:



XXXI*a*. Photograph of root nodules of bean

XXXI*b*. Micro-photograph of bacteria from root nodules of clover



XXXII. Tracklayer at work on the transcontinental line west of Edmonton

Carbohydrates, such as starch (e.g. in bread, potatoes, etc.) and sugar (of which there are several varieties) containing only carbon, hydrogen, and oxygen.

Fats, such as butter, lard, the fat of meat and fish, all animal in origin, and vegetable fats contained in seeds of plants, again containing only carbon, hydrogen, and oxygen, and consisting of an organic acid combined with glycerine.

Proteins contained mainly in meat, eggs, milk, and cheese. They are complex bodies containing nitrogen.

Mineral matter.

The purpose of the carbohydrates is to produce energy. They are converted, ultimately, into carbon dioxide and water—burnt up, in fact, by the oxygen inhaled from the air. The purpose of the fats is also to produce energy, but in this matter the carbohydrates enjoy preferential treatment—they are used first. But fat can be, and is, stored up to be used when carbohydrates are deficient. The purpose of the proteins is to build up the tissues and to repair waste, though when the carbohydrates and fats are exhausted, the proteins may also break down and produce energy. The purpose of the mineral matter is more varied and its consideration may, for the purpose of this chapter, be omitted.

Now let us examine more closely the transformation and destination of each of the first three types of materials. The proteins are broken up in the stomach and small intestine into bodies called amino-acids, of which twenty-three are known though only a few have as yet been fully investigated in relation to the maintenance of life. These amino-acids find their way through the walls of the small intestine into the blood, by which they are carried to all parts of the body and to every one of the million or more cells distributed throughout bone, and muscle, and nerve. In the cells they are reconverted into proteins, but not necessarily the original ones. They are recombined, but not in the same way. All of them may not be used. The cells are fastidious as to both character and quantity. They accept what they need, and reject what they do not require. What is rejected is waste and passes out of the body without performing any service.[1]

If the various proteins are labelled A, B, C, D, etc., and the amino-acids are designated by a, b, c, etc., to r, then A may yield a, b, and k; B may form a, d, f, n, and o; from C we may obtain e, l, m, and r. In other words, different proteins give rise to different amino-acids, though a particular amino-acid may be contained in different proteins. But since the food value lies in the amino-acid all proteins are not

[1] A small quantity of protein reaches the liver and is 'burnt up' like the carbohydrates.

equally valuable. Some, indeed, may be useless. The French Government tried to feed the patients in hospitals on the well-known cheap and easily obtained protein called gelatin, with disastrous results. It is now known that the amino-acids *tryptophane* and *tyrosine*, which are yielded by many proteins and are essential to life, are absent from gelatin. Without these there can be no growth and no repair of wasted tissue.

One important difference between proteins and amino-acids is that the former are colloids and the latter crystalloids. Colloids will not pass through a membrane; crystalloids will. The wall of the small intestine is a membrane, and the result of the action of the digestive juices upon proteins is to convert colloidal substances into crystalline substances which can pass through the membrane into the blood.

The carbohydrates consist of several complex, and several relatively simple, substances. The most complex cellulose, which exists in such varied forms as woody fibre and cotton wool, is not digestible at all. Starch, cane-sugar and lactose, or milk-sugar are converted by the digestive juices into the simpler bodies glucose, fructose or fruit-sugar, and galactose, from milk sugar. These bodies pass into the blood with the amino-acids and proceed to the liver, where they are converted into glycogen, or animal starch, which is stored up and produces energy as required by undergoing conversion into carbon dioxide and water. Though these sugars present a simpler problem than the twenty-three amino-acids their relative value has not yet been worked out with precision.

Fats from animal and vegetable sources contain, as we have said, an organic acid united with glycerine. When such a substance is treated with an alkali, glycerine is liberated and the alkali combines with the acid to form a soap. A similar change is brought about by the digestive juices, and glycerine, fatty acid and soap are formed. These are carried by the blood to the cells, where they undergo reconversion into fat, which is stored up as adipose tissue. Should a man use up energy at a greater rate than it is provided by the carbohydrates in his food, he draws upon his store of fat and becomes thinner, while in a case of starvation he draws upon the protein of his tissues and becomes emaciated.

From experiments upon men working in closed chambers, and measuring the heat produced, the amount of energy required from food can be calculated. This varies from 2,200 calories for a man at rest to 5,000 calories or more for a man engaged in the heaviest labour. For a woman the figures vary from 1,800 to 3,200 calories. By labour, physical labour only is meant, because the experiments fail altogether to measure the energy consumed in brain work. The bulk of this energy is supplied by the carbohydrates, and a little from the fats, though to

what extent fats are necessary to life, and whether there is any difference between them, is still largely a matter of conjecture. It was in the course of an investigation into this matter that the late Sir F. Gowland Hopkins lighted upon a great discovery.

At the end of last century and the beginning of this one, a number of investigators were busy inquiring into the relative value of different proteins. For this purpose rats are generally employed. They only live about three years, and arrive at maturity in 280 days. Consequently, it is possible to find out a great deal about the effect of food materials upon growth by experiments which do not occupy an abnormally long time. To obtain results over the same range with human beings, experiments on a man would have to extend over a period of sixty years. But with rats it is easier to find out, by varying one constituent of the food at a time, the effect of each constituent upon the growth of young, or maintenance of weight in old, rats. The results of such experiments show that for a protein to have any value as food it must be capable of yielding one of the amino-acids, tryptophane, tyrosine, cystine, and lysine, all of these being essential to life.

In 1906 Hopkins fed two sets of rats, one with an artificially prepared food mixture—protein, fat, sugar, and mineral salts—which had the same chemical composition as milk, and the other with the same mixture together with a small quantity of fresh milk. Those without the milk lost weight, and those with the milk gained weight. On the eighteenth day, the diets were changed over, with the result that the rats which were getting thinner began to grow, while those which had formerly grown began to lose weight (Fig. 69). The amount of milk was only two cubic centimetres a day, yet that made all the difference between growth and starvation. The fresh milk contained something without which the most carefully selected artificial diet of (apparently) the same composition as a natural food was incapable of supporting life.

Meanwhile, further evidence came from medicine. Thus, a disease called beriberi, which is a sort of general paralysis, was very common in the East and not unknown in other parts of the world. It had long been recognized that it was in some way connected with the diet. Fifty years ago the men in the Japanese Navy suffered severely from it. During a cruise of nine months there were 169 cases and 25 deaths on a training ship. When the next ship went out the diet was changed at the instigation of Takaki, who had been medical inspector-general of the Navy. The quantity of rice was reduced, and milk and meat were added, so that the food approached more nearly that supplied in European navies. The result was that the only cases of beriberi which occurred were among the 14 men who had refused to eat the new food.

Again, in 1897, Pekelharing in Java had some fowls which became

sick from a disease called polyneuritis, which is very similar to beriberi in man. On inquiry he found that they had been fed with some cooked rice left over from the kitchen. He fed them with ordinary rice in the husk and they speedily recovered. Subsequently he found that polished rice from which the outer skin has been removed would always produce the disease in birds. By investigation in prisons he found that whenever polished rice was given beriberi appeared, but when unpolished rice was used the disease was rare.

Everyone knows of the havoc created by scurvy in mediæval armies

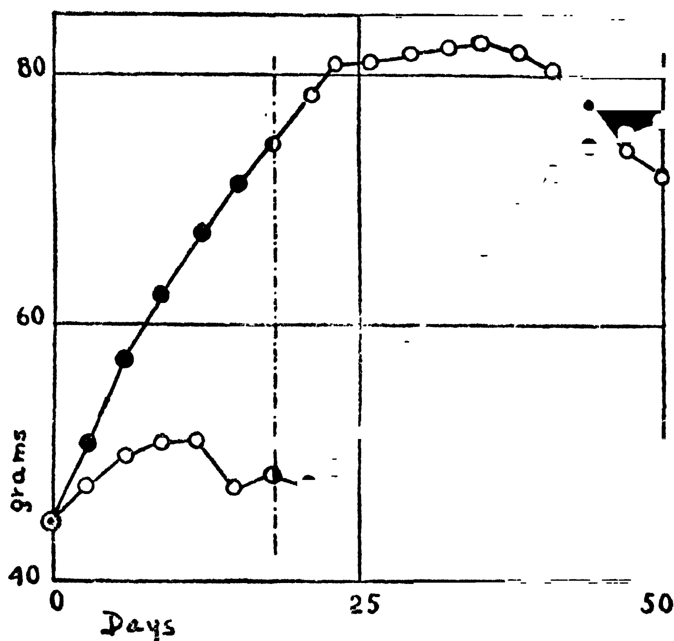


Figure 69. Diagram showing the growth of rats

and among Arctic explorers in modern times. It was rife during the crusades, it was known and feared by the adventurous sailors who took long voyages of discovery in the sixteenth and seventeenth centuries, and it inevitably occurs in countries stricken by famine. Men who suffer from it become dizzy and weak. The gums swell and recede from the teeth. The teeth become so loose that they can be pulled out with the fingers. The remedy for many years has been fresh fruit and vegetables—raw potato has often been used effectively. Experiments on guinea-pigs indicate that the effect of such foods is due to the presence of vitamin C.

It is found that vitamins are destroyed by heating, especially if the heating is prolonged. Thus, Dr. Chick has shown that cabbage or beans heated for one hour at a temperature about that of boiling water lose 70 per cent of their value in curing scurvy.

VITAMINS

Since Hopkins first clearly recognized 'accessory food factors', the number of these which have been discovered has steadily increased, and their nature and role, and their application in medicine, have become more clear. They are organic substances, small quantities of which are necessary for the proper functioning of the cells of the body. They are needed for the promotion of growth in the young, and several of them have been recognized as units in the molecules of enzymes or ferments which have a part in the mechanism of the living cell. If any of these factors, now called vitamins, are absent from the diet, the subject begins to show symptoms of a 'deficiency disease'. Beriberi, scurvy, rickets, pellagra, and xerophthalmia are examples of such diseases, which are due to a deficiency of specific vitamins. These classical examples of deficiency disease are common among populations with a low standard of living. They are not so common in populations with a relatively high standard of living. In the latter case, though vitamin deficiency is widespread, it generally does not take extreme forms, and its effects, though very important, are more subtle, and not so easily recognized.

Hopkins's original name of 'accessory food factors' was changed to 'vitamine' by Funk, in the belief that these factors were chemical 'amines'. When it became evident that many of the factors were not 'amines', the 'e' was dropped, forming the word 'vitamin', which gives to the ordinary person a useful impression of their nature, without suggesting to the chemist any view about their chemical constitution.

By 1952, more than 20 vitamins had been isolated from naturally occurring substances, and identified. In the early stages of vitamin research, they were named by letters of the alphabet. The anti-xerophthalmic vitamin was termed A, the anti-beriberi substance was termed B, and the anti-scurvy substance C. The anti-rachitic substance was called D, the anti-sterility vitamin E, the Danish Koagulations-vitamine K, M after a vitamin necessary for monkeys, and P after a substance which prevents the permeability of cells from being excessive.

Further research showed that pellagra, for instance, was due to a deficiency in preparations of vitamin B. This constituent of these preparations was at first called P—P, or pellagra preventive. Other important individual factors were separated from vitamin B preparations, so these came to be known as the 'vitamin B complex'.

Fourteen factors have now been isolated from this complex, B_1, B_2, etc., up to B_{14}. Many of the factors in this complex differ widely from each other in their effects on the living organism. As the substances become chemically identified, the use of letters tends to be dropped, and the vitamins are referred to by their chemical names; i.e. B_1 is thiamine, B_2 is riboflavin, B_3 pantothenic acid, B_6 pyridoxine, B_{12} cyancobalamin. Others are choline, biotin, inositol, and folic (or pteroylglutamic) acid.

It is rare for a deficiency disease in a patient to be due to the lack of only one vitamin. If there is a deficiency in one, there is generally a deficiency in several others. For instance, those suffering from pellagra are usually deficient in most of the vitamin-B complex, and also in C, the anti-scurvy vitamin, and in niacin.

Most clear-cut cases of deficiency disease are due to poverty, bad food habits, or excessive consumption of highly refined foods. In the richer countries, the far more widespread and less well-defined deficiency diseases are affected by a variety of environmental and bodily states. Peptic ulcers, alcoholism, inability to eat certain foods (allergy), loss of teeth, psychological strain, and many other factors can interfere with vitamin intake. Conditions such as excessive heat or cold, very strenuous physical exertion, delirium, pregnancy and the breast-feeding of babies, increase the organism's demand for vitamins.

Vitamin A is mainly derived from liver, egg yolk, butter, cream and green and yellow vegetables. It is necessary for normal growth of bone and tooth enamel, and the eyes. Night-blindness is an early symptom of A-deficiency. Vitamin A probably has a role in the seeing of bright light, as well as dim light. Particles consisting of vitamin A in combination with proteins may be present in the visual cones, and participate in the process of seeing.

Vitamin D consists of sterols which are anti-rachitic. The most important are calciferol (vitamin D_2) prepared from the activation of ergosterol, a vegetable sterol; and activated 7-dehydrocholesterol (D_3), which is of animal origin. Vitamin D is contained in eggs, sardines and salmon, but not in sufficient quantity. However, human skin contains 7-hydrocholesterol, which can be activated by sunshine. This is why sunshine is effective against rickets.

Vitamin D is extracted from fish liver oils. Cod-liver oil owes much of its value to a high content of vitamin D.

Vitamin E is necessary for successful reproduction in the rat, but no similar effect has as yet been demonstrated in man. It is tocopherol, which exists chemically in the alpha, beta, gamma and delta forms. It is found in certain vegetable oils and cereals, and eggs.

Vitamin K consists of a group of naphthoquinone derivatives which maintain a correct concentration of the very important coagulating sub-

stance in the blood, prothrombin. K_1 is found in pork liver, green vegetables, tomatoes and egg yolk, and K_2 is synthesized by bacteria in the intestine. Vitamin K is abundant in food and its deficiency is due not so much to its absence but to the inability of the organism to ingest it. For instance, the administration of sulfonamide or antibiotic drugs may have killed the bacteria in the intestine which produce K_2, or the taking of liquid paraffin against constipation may have prevented the absorption of K_1 in the stomach and intestines. A deficiency of vitamin K delays the clotting of blood, and leads to hæmorrhage.

Thiamine, B_1, is found in yeast, nuts, pork, egg yolk, legumes, and liver. It is concerned in the building-up of starch and sugar in all of the cells of the body. It is necessary for normal appetite, nerve function and heart action. The classic example of the effect of B_1 deficiency is beriberi.

Riboflavin, B_2, is involved in tissue respiration and the building-up of carbohydrates. One of the signs of deficiency is an itching, burning or roughness of the eyes. It is found in liver, yeast, kidney, eggs, nuts, fish, meat, milk, cheese and green vegetables.

Niacin is a part of two coenzymes concerned in cellular respiration and the building-up of sugar and starch. It is contained in rice, bran, liver, yeast, meat, and nuts.

Pyridoxine, B_6, is present in egg yolks, nuts, legumes, liver, molasses, etc. It is connected with an enzyme system which builds up proteins. A deficiency of it may lead to convulsions in infants.

Folic acid is found especially in green leafy vegetables. A deficiency damages the bone marrow and produces a form of anæmia.

Cyanocobalamin, B_{12}, is required for keeping pernicious anæmia patients in good health. One of the richest sources is liver. Together with folic acid, it is concerned in the formation of pyrimidines and purines, and of nucleoprotein, which is one of the most essential parts of the nucleus of the cell.

Pantothenic acid has a fundamental role in the building-up of many different tissues. A deficiency in animals produces a very wide range of symptoms. It is found in liver, yeast, eggs, broccoli, etc.

Biotin is an important growth-producing substance, whose existence in yeast and bacteria has been recognized since 1901. In man the excreta contain more than the content in the intake of food, showing that the bacteria in the intestine are able to synthesize what the body needs. It can be produced by a diet of raw egg white. A deficiency in biotin produces a scaly skin, pallor and depression.

Choline, and its importance in physiological processes, have long been known, but its status as a vitamin has been recognized only recently. It decreases the rate of deposition, and accelerates the removal of fat. It is concerned in the transmission of nerve impulses, as a

constituent of acetylcholine. It is found especially in cereals, meat and egg yolk.

Inositol, like choline, is concerned in the moving of fat. The two substances acting together are more potent than choline alone.

Ascorbic acid, vitamin C, is the important anti-scurvy factor in citrus fruits, tomatoes, berries, potatoes, etc. It is needed for the sustenance of connective tissues. Its deficiency leads to slow healing of wounds. Lind, who gave the first good clinical account of scurvy as early as 1753, noted that it was affected by cold, damp and fatigue, as well as by dietary deficiency. It has been suspected that the failure of Scott's expedition to the South Pole in 1910 was due in part to vitamin C deficiency. The rations for this expedition were very deficient in this vitamin. Physical exhaustion and frostbite, and failure of a wound to heal, were among the troubles that assailed the party which reached the South Pole, but did not survive.

Through the advances in the technique of organic chemistry, a great deal has been learned about the chemistry of the vitamins. Many of them have been synthesized in the chemical laboratory, as in the classical example of vitamin C. The chemists have succeeded, too, in discovering much about the role of these special chemical molecules in the mechanism of the cell. In some cases, they can be visualized as an essential part in a chemical mechanism necessary for life. So, within fifty years of their discovery, a knowledge of them has led not only to a better treatment of disease, but also to a deeper insight into the mechanism of living processes.

XIII

RAILWAYS

PROGRESS in railways differs according as new or old lines are being considered. In the latter it is not so much a question of invention in the ordinary sense of the word, as improvements in organization to meet new demands and increased traffic, and alterations of the track to reduce the cost of working. The past fifty years has seen a demand on the one hand for long, high-speed, non-stop journeys in England, and for through trains in which people can live for days together when crossing the great continents of Asia and America. On the other hand, the concentration of people in large cities, often within an hour's journey of one another, has required an inter-urban and suburban service of frequent trains; and this service has had sometimes to be established wholly or partially underground. It will be convenient first to consider very briefly

TRANS-CONTINENTAL LINES

For mammoth engines, huge loads, and enormous distances, the inquirer must turn to the great continents of the old and the new world. North America was at first peopled only along the Atlantic seaboard and the Pacific slope. Until the railways came, the wide expanse of prairie and the stupendous heights of the Rocky Mountains separated the settlers in the east and west more effectually than if they had been divided by the rolling sea. The difficulties met with in the construction of these lines were enormous. On the one hand the directors, realizing that for a time the business must be conducted at a loss, demanded cheapness. On the other, great natural obstacles required an expensive scheme. In the low-lying areas there were extensive tracts of bog to be crossed, and wide streams to be bridged over. But the Rockies provided the most serious problems. Long detours had to be made to avoid the tunnelling, and the trains wound backwards and forwards along the mountain-sides as they rose towards the summit. To save distance and

time, steep gradients were included, and most of the Canadian and American Companies have spent millions in later years in relaying the line and driving tunnels to avoid detours and slopes that required three or four engines to mount them. In such country, indeed, it is often safer underground than on the surface; for mile after mile has to be protected against avalanches and the peril which accompanies their fall.

In another way, too, the local conditions influenced the plans of the engineers. Timber was plentiful and cheap, and masonry and steel were scarce, remote, and expensive. So abrupt dips in the land and deep gullies through which foamed mountain torrents were spanned by wooden trestle bridges. As the country became more thickly settled and business grew, these bridges were replaced by structures of masonry and steel, allowing for heavier loads, higher speeds, and a longer life; while as opportunity offered the single track was doubled between important stations.

The construction of the track across stretches of rolling prairie has provided engineers with scope for their ingenuity in mechanical track-laying, and several ingenious machines for this purpose have been used during the past ten years or so. The one illustrated in Plate XXXII was employed on the Grand Trunk Railway of Canada. A train is made up of the tracklayer, followed by half a dozen flat trucks carrying rails, then the engine, and lastly a number of trucks carrying sleepers. Alongside the train is a trough with rotating rollers at the bottom, and the sleepers, pitched into this from the trucks in the rear, are carried along and tumbled out at the side of the track. Here they are rapidly placed in position, while from the huge overhanging front of the tracklayer rails weighing over half a ton each are slung into place and spiked to the sleepers. The track is then ballasted and is ready for use at first by light loads and within two or three months for heavy loads at high speeds. In this way progress has been made at the rate of 5 miles per day. Supposing the sleepers are only 3 ft. apart from centre to centre, and that the work could proceed continuously, this would involve fixing the astonishing number of 8,800 sleepers per day.

But the character of the land on the east presented its own special problems. There are numerous low divides from which the water drains but slowly, and when the spring sunshine disperses the winter's frost, the land becomes a swamp. It is perhaps not out of place to note here that this feature determined the original native forms of locomotion; the birch-bark canoe enabled the water-courses which threaded the morass to serve as the highway in summer, and snowshoes and sledges became imperative in winter. Wheeled vehicles were introduced on the North American Continent by Europeans.

TUBE RAILWAYS

The pioneer railway engineers soon learned to pierce their way through great mountains, and the earlier volume contains an account of the way in which the Mont Cenis and St. Gothard tunnels were constructed. A different set of problems is met with in tunnels under water, of which those under the Severn, Mersey, and Thames are examples. As compared with either of these the construction of a shallow tunnel only a few feet below the surface of dry ground is a comparatively easy matter. But the types for which the early years of the twentieth century will be famous are the spiral tunnels in the Alps and the Rockies and the tube railways driven deeply beneath the earth's surface in London. For such enterprises the way had been paved by nineteenth-century

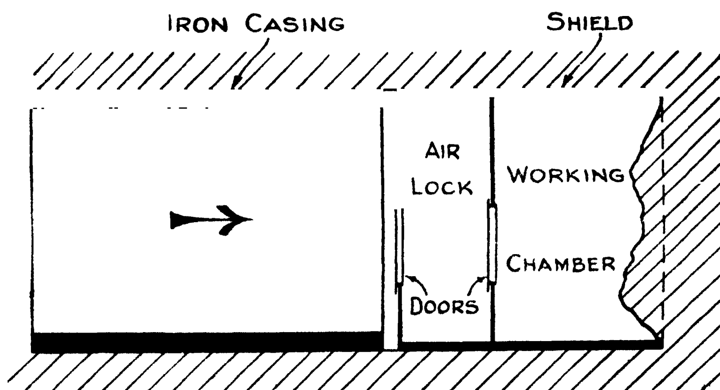


Figure 70. Greathead Shield and tube

experiments, and today they are entered upon with the confidence born of the consciousness that instruments of precision, and tools of marvellously increased dexterity and power, will enable the work to be accomplished at a fraction of the cost that would have been involved fifty years ago.

The invention which banished many of the difficulties of working under water or through water-bearing ground was the Greathead Shield, named after the famous civil engineer, who converted what had previously been a suggestion into a practical device. It consisted of a large iron tube equal in diameter to the external dimensions of the tunnel to be driven. The front end had a cutting edge, and the back was closed by two parallel partitions a few feet apart, fitted with airtight doors (Fig. 70). Compressed air was driven into the front end and this held back the water. The space between the two partitions formed an

air lock, so that men could enter, and material could be removed, without reducing very much the pressure in the main chamber. As the material in front was excavated the shield was forced forward by hydraulic pressure, and the tunnel was lined with iron as it proceeded.

The tunnels under the Severn and the Mersey were not constructed in this way, and the difficulty of dealing with percolating water was enormous. The first named took no less than thirteen years to complete. Both were opened in 1886. In addition to the main tunnel which in each case slopes steeply towards the middle of the river, lower tunnels sloping in the opposite direction had to be made to draw off the water, see Fig. 71. Three times was the Severn tunnel flooded, the water entering at such a rate that the pumps were utterly unable to cope with it.

The use of compressed air for shaft-sinking and tunnelling had been

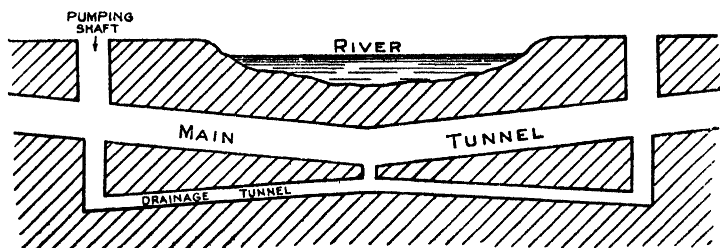


Figure 71. Typical river tunnel, old plan

patented by Lord Cochrane in 1830, but it was not actually used for the latter purpose until 1869, when P. W. Barlow and J. H. Greathead constructed the Tower footway under the Thames.

The value of the shield was thoroughly demonstrated by the construction between 1886 and 1890 of the City and South London Railway, which, under the direction of J. H. Greathead, was driven through solid London clay, 90 ft. below the surface. This was the first really deep tunnel in the world, and the nature of the material through which it was driven would have rendered any other method impossible.

One of the most interesting of the London tubes is the Hampstead line, which has aided so much the development of a residential district north of London. The depth varies considerably owing to the varying level of the surface. At one of its extremities the tube emerges from the surface, but the station at Hampstead is 192 ft. deep, while at a point 300 yd. farther north the line is 250 ft. below the level of Hampstead Heath. The tube is 11 ft. 9 in. in diameter along the straight, 12 ft. and 12 ft. 6 in. on curves, and 21 ft. 2½ in. at the stations. So great is the accuracy with which this and similar tubes are driven that it is no un-

common event for both shields (one starting from each end) to meet edge to edge. They are then left in to form part of the iron lining. In the case of the Hampstead Tube, when the shields met in December, 1903, the following small inaccuracies were observed:

Error in direction	$\frac{1}{4}$ in.
Error in level	$\frac{1}{8}$ in.
Error in length	$\frac{7}{8}$ in.

A cross-over on the Central London Line is shown in Plate XXXIII.

These tunnels are small in diameter compared with some which are not used for railway traffic. The Blackwall tunnel, for example, is 24 ft. 3 in., and the Rotherhithe tunnel is larger. The latter is 4,800 ft. long, and runs for over 1,400 ft. under the Thames. At one point it is only 7 ft. below the bed of the stream, and it was impossible to follow the usual practice of making a 'blanket' by tipping earth over the spot, owing to the inconvenience this would have caused to navigation. A railway tunnel under the East and Hudson Rivers has some similarity to that at Rotherhithe in its proximity to the bed. The principal objection is, of course, the danger of a 'blow-out', and on one occasion a workman was actually expelled right through the bottom of the river to the surface. It is remarkable that after such an experience he should have lived until the next day.

Valuable, however, as was the Greathead Shield in enabling these subterranean corridors to be driven at a reasonable cost, not a little of their development has been due, as will appear from a perusal of Chapter XIV, to electric traction. Ventilation is at times difficult in deep subways, and by no possibility could the smoke of locomotives have been extracted from the deeper tubes.

One of the disadvantages of tube railways is the trouble of getting to and from the platforms. Steps are very inconvenient, especially for elderly or stout people, and there are many to whom the sensation of travelling up or down in a lift is objectionable. At many of the London stations—the Liverpool Street Station of the Central London Line was an early example—escalators have been erected. These are moving stairs which work in inclined tunnels. Those at Liverpool Street rise 40 ft. and the speed is 90 ft. per minute. The four of them will convey as many passengers as ten of the ordinary lifts in use at the same station. The principle upon which they work is very ingenious, and by the courtesy of the Otis Elevator Company the author is able to include a description of the mechanical arrangements. The stairs are attached to a continuous chain which passes over a sprocket or toothed wheel at the top and bottom of the incline. The 'tread' or standing portion of each step is supported on a wheeled truck and the two front wheels are closer together than the hind ones. Two pairs of rails are required—one pair

of narrow gauge for the front wheels and one pair of wider gauge for the hind wheels. When the rails are on the level the 'treads' follow one another closely, forming a moving platform, but at the foot of the incline the outer rails rise before the inner as shown in Plate XXXIV*a*. In this way the tread always remains horizontal and the steps follow one another up the incline to the top, when the outer rail becomes level first. On either side is a flexible handrail, which moves at the same rate as the steps, though the motion is so steady that there is really no need for it.

The escalators usually installed have a carrying capacity of more than 10,000 people per hour. In London they are to be seen at Liverpool Street, Earl's Court, Paddington, and most of the other stations underground. These will carry over 2,000,000 passengers a day.

THE MODERN LOCOMOTIVE

The great railway engines of today—a perennial source of interest during the period of boyhood—have not altered much in outward form during the last eighty years, but they have increased very considerably in size and power. A typical engine of 1870 had a weight on the driving wheels of 15 tons; the Great Bear of 1908 a weight of 60 tons. The pull of the former was over 10,000 lb.; that of the latter was over 26,000 lb. Eighty years ago the weight of a Great Western express, excluding the engine and tender, was about 60 tons, whereas a modern British train may weigh 650 tons.

Increased power in any engine is generally obtained by increasing the size and efficiency of the boiler and the size and number of the cylinders, in addition to the various devices for preventing waste. On a locomotive, however, the size of the boiler is limited. If it is made higher the existing bridges would be in the way; if made of larger diameter the driving wheels would have to be reduced in size, and though the largest driving wheels do not permit of the highest speeds there is a lower limit beyond which it is not desirable to go. With the existing gauge of 4 ft. 8½ in. larger boilers cannot well be employed, so that various methods are adopted to increase efficiency, and these may briefly be considered in turn.

The draught in a locomotive is caused partly by the air which enters the front of the ash-box, owing to the motion of the train, and partly by the discharge of exhaust steam into the smoke-box. The earlier boilers were made with short smoke-boxes, but it has been found that a larger space under the chimney acts as a sort of reservoir, and the draught is much steadier. If one of the older engines of any of the railways be compared with a modern engine, the extended smoke-box will be quite noticeable.

Perhaps no development in locomotive construction is more striking than the spread of superheating. The general principles upon which the superheater works and the way in which it effects economy in the engine have been described in Chapter III. On the locomotive the chief difficulty has been to arrange a considerable length of tubing in the limited space available. In some cases the smoke-box has been used, but in the latest form of the Schmidt superheater the relatively narrow tubing through which the steam passes on its way to the cylinder is contained in a number of larger flues leading from the upper part of the fire-box. The drier steam at a higher temperature leads to an economy of 10 to 15 per cent, though considerably higher figures are claimed.

When the boiler has reached the largest size that the bridges and gauge will permit, and when it has been equipped with the most efficient devices for improving the draught, for heating the feed-water, and for superheating the steam, the only other direction in which greater economy can be obtained is in the utilization of the steam. One method is to 'compound', and to cause the steam to expand over a greater range through two, three, or four cylinders successively. The compound engine on English railways has had a chequered career.

The Continental and American Railways are fairly unanimous on the matter, and two and four-cylinder engines of this type are the rule rather than the exception on the big lines. It is claimed on their behalf that a saving, which may amount to 20 per cent, results from the practice, and that this more than compensates for the extra cost of construction and maintenance. Some difficulty arises in starting. In the ordinary engine, steam goes direct to each cylinder, and the whole effect of the boiler pressure can be exerted to overcome the starting resistance. But in the compound engine the steam goes through the cylinders in series, and sufficient power for starting cannot always be obtained on the small high-pressure pistons. A special arrangement by which steam can be sent directly into both cylinders at first is therefore adopted, and this increases the complexity of the engine.

The modern classification of locomotives is based on the number of wheels, and the extent to which they are coupled. The front is supported by a pony truck, or bogie carriage, having two or four small wheels, while the main weight of the boiler is carried by two, four, six, eight, or ten larger wheels, which are usually coupled in order to increase the grip on the rails. The cab, too, is carried on none, two, or four bogie wheels. The usual arrangements are shown in Fig. 72, and the description under each will render the diagram self-explanatory.

Locomotives in Great Britain differ materially from those in other parts of the world. Transcontinental lines such as the Canadian Pacific Railway use very powerful locomotives for drawing heavy freights.

On many railways in new countries the track is laid to a narrow gauge, and contains sharp curves and steep gradients necessitated by cheapness of construction. For the same reason relatively light rails are used. Of the locomotives which have been designed to meet these conditions none have been more successful than those of the famous Garratt type of articulated engines. Messrs. Beyer, Peacock and Company, built a number for use on the State railways of Western Australia. The gauge is 3 ft. 6 in., some of the curves are only of 5 chains radius, and the

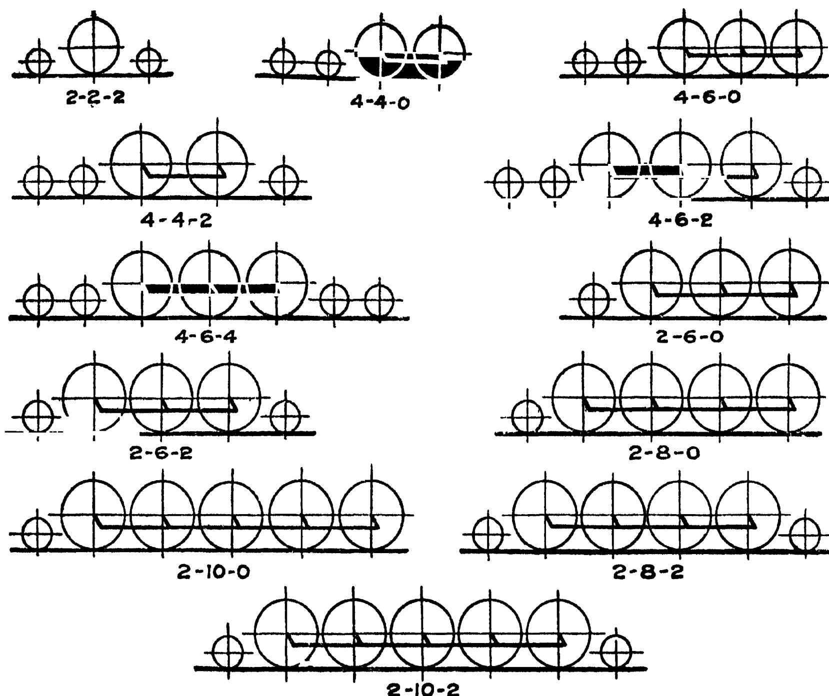


Figure 72. Classification of locomotives

gradients are as steep as 1 in 22. It was stipulated in regard to the first six that the load on each axle should not exceed 9 tons, and that the tractive force at 75 per cent of the boiler pressure should be not less than 21,000 lb.

The boiler is carried on a frame resting upon, and pivoted to, the engine frames at each end. This double joint enables the locomotive to take sharp curves without grinding, or the heavier portions overhanging so far as to endanger the stability. The distance between the pivots is 25 ft. The absence of wheels under the boiler enables it to be designed

independently of the restrictions which usually hamper the locomotive engineer. The engines are not compound, but Schmidt superheaters are fitted in the last seven. The two tenders carry 2,000 gallons of water and 3 tons of coal. When full the total weight is just under 70 tons, and in no case does the load on one of the eight axles exceed 9 tons 7 cwt.

Recently, diesel electric locomotives have been introduced on these railways; an illustration of a 1,105-h.p. locomotive of this type is shown.

Another interesting type of locomotive is illustrated in Plate XXXV. This is one of a number which have been constructed by the famous Baldwin Locomotive Works for the Chesapeake and Ohio Railway, and are used to haul trains weighing nearly 700 tons over the Alleghanies. The main frame is of vanadium steel and the construction is adapted for heavy work. A very good view is obtained of the Walschaert valve-gear, which is preferred on the Continent and in America to Joy's, which is used on British railways.

A monster engine made by the same company was built for the Southern Pacific Company, a compound four-cylinder engine with an oil-fired boiler. The engine and tank-tender measure over 90 ft. long, and the latter carries 10,000 gallons of water and 3,200 gallons of oil. Both this and the former engine are fitted with superheaters—the former with a Schmidt, and the latter with one of the Baldwin smoke-box type.

THE GAS-TURBINE LOCOMOTIVE

Though the reciprocating steam locomotive still dominates the world's railways, the introduction of other types, such as the electric and the diesel-engined locomotives has made considerable progress. One of the most recent innovations is the gas-turbine locomotive.

One of these, the No. 18100, was designed and built for the Western Region of British Railways by Metropolitan-Vickers Electrical Co. Ltd. An external view of No. 18100 is seen in Plate XXXIV*b*.

Its capacities were stipulated by the Chief Mechanical Engineer of the Great Western Railway, who had in mind the needs of a locomotive for operating the express trains on the London–Plymouth run. He required a locomotive which would give a maximum speed of 90 m.p.h., hauling a maximum load of 18 coaches weighing 650 tons, and capable of negotiating a short gradient of 1 in 36, and more than 2 miles of 1 in 42.

A locomotive capable of this duty should have a maximum tractive effort of 60,000 lb., and a continuous rated tractive effort of 30,000 lb.

The designers took into consideration these requirements, and others, such as the ability of the locomotive to develop these efforts in hot as well as mild climates, and at high altitudes as well as sea-level, where the air is at higher temperature or reduced pressure.

The leading particulars of the resulting design were as follows:

Mechanical Type	Double bogie
Continuous Rating of Turbine	3,000 h.p.
Number of Axles	6, all driving
Weight in Working Order	130 tons
Maximum Service Speed	90 m.p.h.
Maximum Tractive Effort	60,000 lb.
Continuously Rated Tractive Effort	30,000 lb.
Length of Buffers	67 ft.
Width	9 ft.
Height from Rail	12 ft. 10 in.
Wheel Diameter	44 in.
Fuel	Gas Oil

In order to get the maximum tractive effort of 60,000 lb., driving on all of the six axles of the two bogies was necessary. Each of the six axles was driven by its own electric motor, drawing current from a dynamo driven by the gas turbine.

In tests, Locomotive No. 18100 has hauled a 17-coach train at speeds of 85 m.p.h., and has started an 18-coach train from rest on a 1 in 42 bank, without apparent effort.

The body-structure of the locomotive has a driving-cab at each end. It bears the power-plant, and is carried by two bogies, each with six wheels, through the intermediary of resilient rubber universal joints. Each of the six bogie axles is driven through a single reduction gear by a traction motor suspended on the axle and a support on the bogie frame.

The gas-turbine runs at 7,000 r.p.m. at full load. It drives two shafts through a single-reduction gearing, at 1,600 r.p.m. when running at full load. One of these drives two main electrical generators in tandem, and the other a third main generator, an auxiliary generator and an exciter. The three main generators produce current for driving the six traction motors on the axles.

The turbine reduction gear, generators, fuel and lubrication pumps are mounted as one power-unit on a common bed-plate.

When the locomotive is running with its turbine developing 3,000 h.p., about 150 h.p. is lost through friction in the reduction gear and the requirements of the auxiliary equipment. Thus 2,800 h.p. reaches the electrical transmission system. This has an efficiency of 86 per cent, so about 2,450 h.p. is delivered by the locomotive at the rails.

The thermal efficiency of the turbine is about 19 per cent. When the losses due to the reduction gear and the electrical transmission are allowed for, the overall thermal efficiency of the locomotive is 16 per cent. After allowing 75 h.p. for driving the auxiliaries, the traction power available at the wheels is about 15½ per cent, which is equivalent to the consumption of 0·88 lb. per horse-power hour, when the turbine is

running at full power. At half-power the consumption rises to 1·3 lb., and the efficiency accordingly falls to 10½ per cent.

The gas-turbine locomotive has a much higher thermal efficiency than the reciprocating steam locomotive, and its maintenance cost is lower for equal work done, if its high performance can be fully utilized through suitable traffic conditions. These advantages then offset the higher capital cost.

The gas-turbine locomotive has advantages over the diesel locomotive for higher powers. It is much lighter, and can do the work of two diesel locomotives of double the weight. This, together with the much easier maintenance of its simpler rotary machinery, outweigh the advantage of the higher thermal efficiency of the diesel engine.

Air is compressed and flows into combustion chambers, where it is heated through the burning of fuel injected by nozzles. The compressor has fifteen stages, and increases the pressure by 5·25 times, when running at 7,000 r.p.m.

The combustion chamber is made of heat-resisting steel, and has six flame-tubes parallel to the axis. The fuel pumps inject fuel at a pressure of about 650 lb. per sq. in. into the tubes.

The air and gaseous products of combustion, now at a very high temperature, are delivered into the turbine. This consists of five stages.

The turbine is made of special heat-resisting materials. The casing is made of an austenitic steel casting, and the rotor is forged out of austenitic steel. The fixed and moving blades in the first stage are made of the alloy Nimonic, in the intermediate stages of Nimonic and austenitic steel, and in the last two stages of molybdenum steel.

The reduction gear consists of a central shaft from the turbine carrying a pinion. Gear-wheels on both sides transmit the drive to the two shafts of the generators. The pinion is made of case-hardened steel, the profiles of the teeth being ground to shape after hardening. The gear-wheel rims are made of chromium-molybdenum steel.

The three main generators consist of self-ventilated direct-current six-pole machines. The continuous rating is 1,100 amp., 666 volts, 1,600 r.p.m. The maximum voltage is 825 volts, and current, 2,200 amp.

The six traction motors are each separately ventilated four-pole series machines. Their continuous rating is 550 amp., 666 volts, 706 r.p.m., with maximum current of 1,100 amp. and voltage 825 volts.

The drive to the axle is through a single reduction spur gearing of ratio 21 : 58. The gear wheel is made torsionally resilient by mounting the rim separately from the centre through a series of resilient rubber bushes. This torsional resilience cushions the transmission of mechanical shocks communicated to the armature of the motor when the wheels pass over joints in the rails. The general reduction of stresses

thereby makes for the smoother riding of the locomotive, and reduced maintenance costs.

Most of the numerous auxiliaries are driven by 110-volt direct current from the auxiliary generator. This feeds the large accumulator battery, which consists of 48 lead-acid cells of 384 ampere-hour capacity.

Heat carried away from the turbine bearings and reduction gear in the lubricant is dissipated by an air-blast on pipes through which the lubricant circulates. The air-blast is produced by a fan driven at 1,480 r.p.m. from a 10-h.p. motor run on current from the auxiliary generator.

An air-compressor driven by an 8-h.p. motor supplies compressed air at 100 lb. per sq. in. for operating locomotive brakes, warning horns, window wipers, devices for blowing sand on the lines, etc.

Two 11·25-h.p. motors drive centrifugal blowers for delivering cooling air to each of the six traction motors.

In addition to these auxiliaries driven directly off the auxiliary generator, there are many others driven through the medium of current from the battery.

Fuel and lubricant are supplied to the turbine by a 10-h.p. motor driven from the battery. A duplicate set is carried, in case one should not function properly.

The fuel pump can supply 7·5 gallons per minute at 650 lb. per sq. in., and the lubricant pump 70 gallons per minute at 50 lb. per sq. in. A small $\frac{1}{4}$-h.p. auxiliary pump delivers fuel from the fuel tank under the locomotive frame to the main fuel pump. Another $\frac{1}{4}$-h.p. pump supplies lubricant to the turbine and gearings during the cooling period after the turbine has been shut down.

Two 4-h.p. motors drive two reciprocating four-cylinder exhausters for keeping a vacuum to operate the vacuum brake equipment in a train.

All of these run off the battery so that they can be operated when the turbine itself is not running.

In addition to these, the locomotive carries a boiler for providing steam for heating the train. It is oil-fired, with vertical fire tubes, and delivers 1,500 lb. of steam per hour, at 80 lb. per sq. in.

Large air-filters are provided for cleansing the air before it is drawn into the turbine: 40,000 cubic feet per minute are passed through a dry fabric in order to remove the dust.

Besides warning-horns and window-wipers, the driving cab contains foot-warmers, electric food-heaters, and a system of ventilation and heating. The ventilation air is drawn from the supply for cooling the traction motors. It can be electrically heated, and the driver can manipulate a 'Punkah louvre' set high at the back of the cab, to secure the desired quantity, direction and temperature of air.

The fuel and water are carried in a long elliptical tank slung under the frame. The tank is divided transversely into two compartments, one

holding 995 gallons of fuel, and the other 620 gallons of water. If water is not needed, both divisions can be used for fuel.

Most of the auxiliary equipment is grouped near the two end driving cabs, and to the adjacent ends of the power unit.

The main levers for controlling the locomotive have been reduced as far as possible to resemble in number and function those in the conventional steam locomotive. This enables the regular engine drivers to take over the gas-turbine locomotive with the minimum of specialized training.

In order to do this, it has been necessary to make the machine largely self-governing and automatic, and this has required a complicated system of control. As a result, the driver is able to control the locomotive with the minimum of concern and responsibility for the functioning of the power plant and the auxiliaries.

When the driver takes over the locomotive in shed or siding, he performs two simple operations; he operates the key switch, and presses the button for starting the turbine. A green light appears one minute later, indicating that the turbine is now running at idling speed, at which the driver switches on the brake compressor and exhausters.

The locomotive is ready for service after about five minutes' warming-up from cold.

The successive steps after the driver has pressed the starting button are entirely automatic, and are governed by a timing or sequence controller driven by an electric motor.

The auxiliary fuel pump starts, and then the main fuel and lubrication pump is brought into action. This is followed by the lighting of the igniters in the flame-tubes. The automatic starting valve begins to open, and the turbine starts to rotate.

The main generators are set going as motors by current from the battery, and accelerate the turbine until it attains a self-sustaining speed. By the time it reaches 1,000 r.p.m., fuel is delivered through idling jets into the combustion chamber.

The combustion of the fuel assists the acceleration, until at 2,500 r.p.m. the main generators are automatically cut out, and the turbine accelerates under its own power to 4,000 r.p.m. The time taken from pressing the starting button until the turbine starts is about 10 seconds. Twenty-five seconds later the main generators are cut out, and 30 seconds after that, idling speed is reached.

About 10 minutes' warming-up at idling speed is necessary before full power can be taken from the locomotive.

When the locomotive is shut down after running at full load, it is run for 10 minutes at idling speed, to allow it to cool down gradually. After the turbine stops, an automatic motoring arrangement rotates the turbine for a few seconds every 3 minutes, in order to equalize the cooling stresses.

The turbine and generator are governed automatically to give, at the most efficient turbine speed, the output of power selected by the driver to deal with his load.

In case of abnormal conditions, such as excessive turbine speed or gas temperature, hot bearings, or fuel or lubricant deficiencies, there are over-riding controls which supersede these normal automatic controls.

In addition to the starting operations, the automatic control performs ten other functions during normal running. It starts the lubricating oil cooler fan, the traction motor blowers, the recharging of the battery, opens the fuel valve in accordance with the driver's power lever, adjusts the field strengths of the main generators and traction motors in accordance with the driver's demands and the changing speed of the train, limits the tractive effort if the locomotive speed is too low for the power selected, adjusts the turbine speed to the one which is most economical for the power demanded, regulates fuel consumption in order to avoid turbine over-heating, controls the auxiliary lubricating oil pump to avoid excessively hot bearings, runs the turbine at intervals after shutting down to prevent rotor distortion during cooling.

The general method of exercising these controls depends on the relation of each quantity to be regulated to a proportionate voltage. Control relays and servo-mechanisms are used to adjust the proportionate voltage to the appropriate value, and this ensures that the quantity to be regulated will be in turn adjusted to that value.

Emergency controls are provided to deal with such situations as when the battery is too run-down to start the turbine. In this case, the locomotive is towed or pushed by another locomotive. The traction motors then become generators, and supply current in place of the battery.

If the automatic control of the output of power in response to the changing speed of the train breaks down, the assistant driver can perform the function of a governor by keeping the turbine speed roughly constant, by manipulating a manual fuel valve.

The body and the underframe are built as a single unit, almost entirely by welding together separate parts.

The bogies are welded from plates. Each complete bogie frame and each main welded section of the body structure are relieved of stress by annealing in a furnace.

The driving cab walls and roof mounted at each end of the underframe, consist of separate welded aluminium alloy structures.

The gas-turbine locomotive No. 18100 is the most powerful locomotive which has yet been built for railways in Britain. The combination of great power under complete and flexible control, with clean and comfortable working conditions, and economical operation, represents a striking advance towards the modern aim of placing the possibilities of technology at the service of mankind.

RAILWAY STANDARDIZATION: LOCOMOTIVES

The most striking development on British Railways after they were taken over by the state in 1948 was the extension of standardization. The new national organization found itself with a range of locomotives of more than four hundred different designs.

These four hundred heterogeneous locomotive types are ultimately to be replaced by twelve standard designs. The building of 160 locomotives was planned for 1951, according to six of the new standard designs. These were to be constructed in the railway works at Crewe, Derby, Swindon and Brighton, while old types were to be built and repaired at other works.

All the new designs of locomotive are for mixed traffic purposes, so as to give the maximum amount of inter-availability. The two bigger designs of the 4–6–2 or Pacific type are inter-available for express passenger or fast freight trains.

The British Railways designers worked for two years on the plans for the new locomotives. The best practices from all Regions were studied and compared, so that the best features could be chosen from each, and combined in the final designs. Attention was devoted to ensuring the maximum ease for giving access to servicing and repair, for economy in coal consumption, and a high degree of inter-availability of parts. A special effort was made to improve the amenities for the drivers and firemen: the footplate crews; and advice on this point was sought from the trade unions and representative enginemen.

The largest possible grate area is provided for each engine. Roller bearings are fitted throughout on the largest types. All tenders have roller bearings, and manganese liners are fitted to all coupled axle-boxes.

The new mixed traffic 4–6–0 is illustrated by locomotive No. 73000 (Plate XXXVI*c*).

The new 4–6–2 locomotives are designed to be capable of undertaking the duties of, and working over all routes now used by such types as the Castle, West Country 4–6–2's, etc. (Plate XXXVII*a*).

These locomotives have two cylinders 20 in. in diameter, and 28 in. stroke, and coupled driving wheels 6 ft. 2 in. in diameter. The boiler pressure is 250 lb. per sq. in. and the locomotive can exert a tractive effort of 32,150 lb. The engine and tender, loaded with seven tons of coal and 4,250 gallons of water, weigh altogether 141 tons 4 cwt.

Other new standard types introduced in 1951 were a lighter 4–6–2 type No. 72000, a lighter 4–6–0 type No. 75000 planned to replace, with a greater range of availability and with full modern equipment, numerous classes of 4–4–0's now becoming obsolescent.

This Standard Class 4 has two cylinders of diameter 18 in. and 28 in. stroke, 5 ft. 8 in. diameter driving wheels, a boiler pressure of 225 lb.

per sq. in. and a rated tractive effort of 25,515 lb. Loaded with six tons of coal and 3,500 gallons of water, the engine and tender altogether weigh 110 tons 1 cwt.

In addition, two new tank engines, No. 80000: a 2–6–4T for residential passenger traffic, and No. 82000: a 2–6–2T for light passenger, freight and shunting work, were introduced in 1951.

A 360-h.p. 0–6–0 Diesel electric shunter locomotive is being made in large numbers for hump and flat shunting. It weighs, in working order, 47 tons 5 cwt., and has a maximum speed of 20 m.p.h. The power unit consists of a standard six-cylinder four-stroke diesel engine made by the English Electric Co. Ltd. It is direct-coupled to a 6-pole 206 kW. D.C. generator.

PASSENGER COACHES

The standardization of passenger coaches was begun with the introduction in 1951 of twelve types of new coaches of standard dimensions, which would allow them to be run on all of the principal lines. They were of all-steel construction of increased strength, with automatic couplers for increasing the safety both of passengers, and of the railway staff who have to couple up coaches and locomotives. Improver bogies were introduced, in order to provide better riding.

The seats in the compartments of the corridor coaches are normally three-a-side. The upholstery is selected from nine different patterns of figured moquette.

Luggage compartments are partitioned off from the corridors, and are under the guard's observation.

The guard's compartment is equipped with a desk and cupboard unit, a food warmer and steam heater. There is a swivel seat, from which the guard can observe signals and landmarks through a periscope.

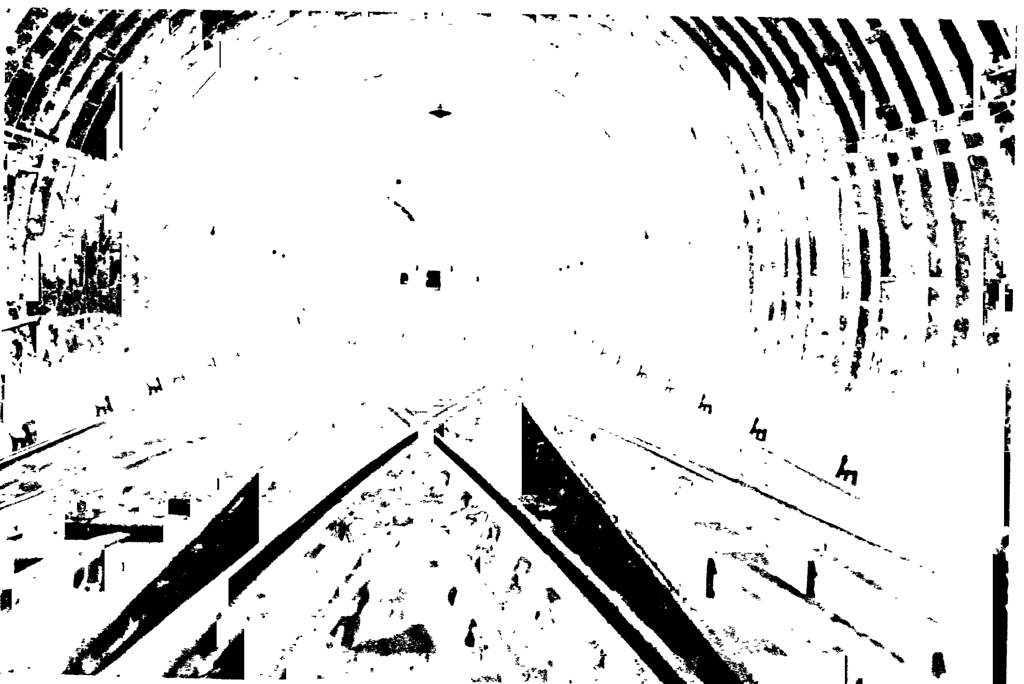
The cooking in the new kitchen cars is done with anthracite and electricity.

It was planned to construct 1,189 main line corridor coaches of the new type in 1951, as the first step in standardization. The next step will deal with non-corridor coaches for steam and electric services. New designs are being prepared for first- and third-class sleeping coaches.

The 1951 building programme also included 1,252 other passenger train vehicles of existing types. In the summer of 1951, for the first time since the Second World War, the numbers of passenger coaches available, i.e. 43,000, was about the same as in 1939.

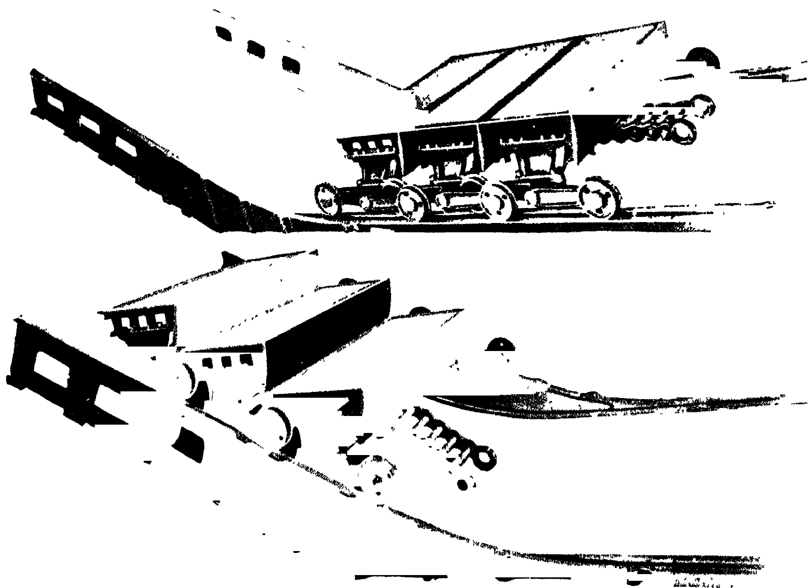
GOODS WAGONS

The extension of standardization to rolling stock on British Railways is an immense problem. On 1st January 1948, the new organization



(London Transport)

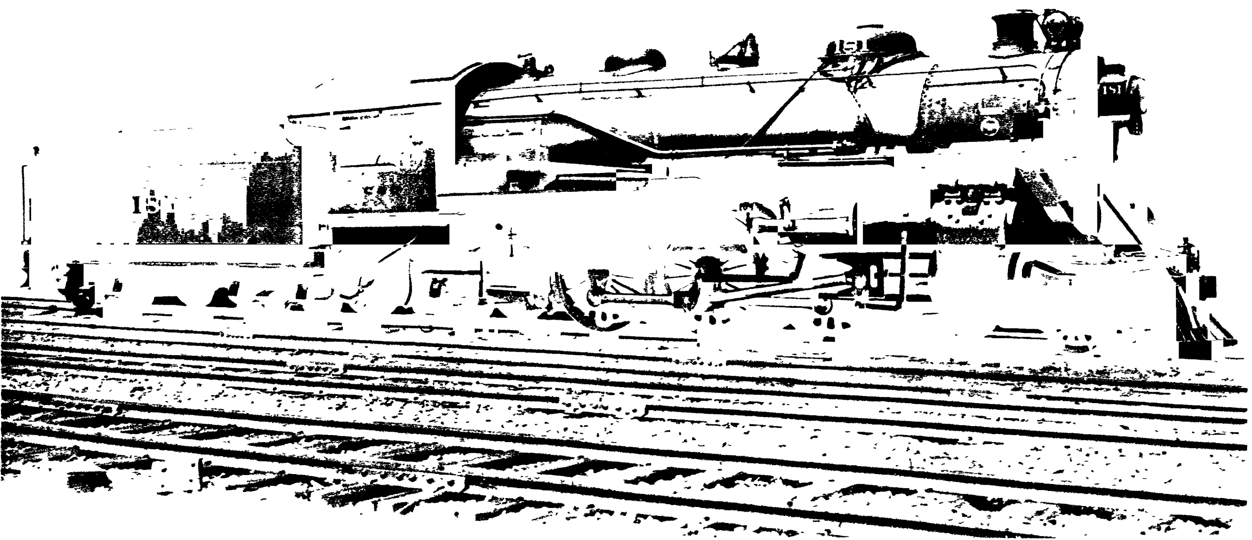
XXXIII. Cross-over on the Central London Line



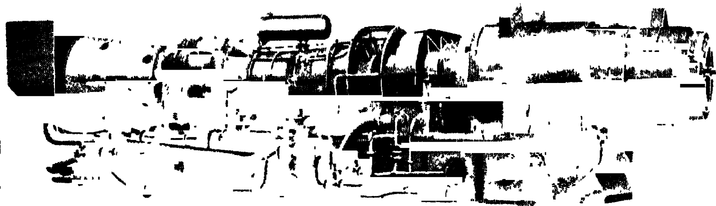
xxxiv*a*. How the step escalator works



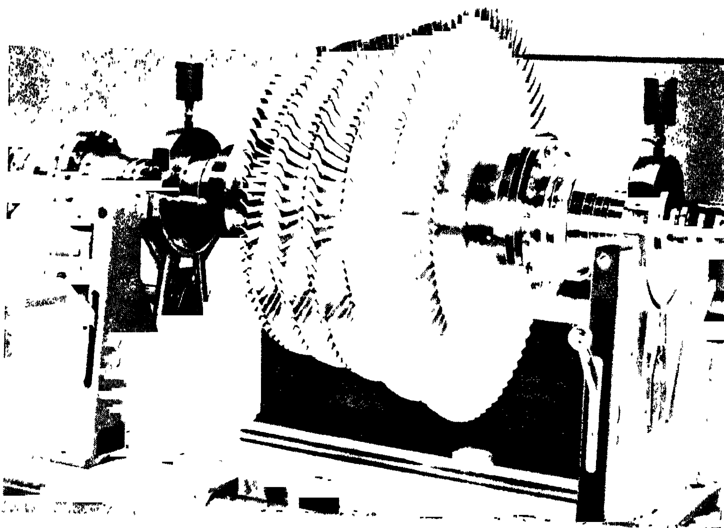
xxxiv*b*. No. 18100, a gas turbine locomotive designed and constructed by Metropolitan Vickers for British Railways (Western Region)



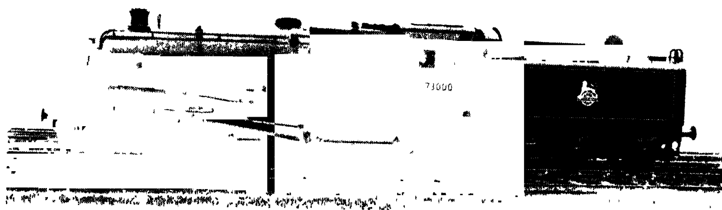
xxxv. A huge locomotive on the Chesapeake and Ohio Railway



XXXVI*a*. The complete power unit of No. 18100



XXXVI*b*. The motor unit for the gas turbine of No. 18100



XXXVI*c*. No. 73000, British Railways Standard Class 5, a 4–6–0 mixed traffic tender locomotive

found itself with 1,200,000 wagons formerly owned by railways or private firms. No less than 480 different designs of wagon were then being manufactured, so plans were immediately put in hand for designing a small number of standard types which could deal with all the different kinds of traffic carried.

SUMMARY OF MAIN TYPES OF WAGON ON BRITISH RAILWAYS

Type	*Number operated*
Open	305,616
Covered	141,140
Mineral (not hoppered)	542,099
Mineral (hoppered)	58,692
Special	2,309
Cattle	13,079
Steel carrying	43,743
Fish	4,258
Freight Brake Vans	14,882
Containers	24,628

Many old wagons of low-carrying capacity had grease-lubricated axles, which involve operating difficulties. It was decided to withdraw all these as quickly as possible, and replace them by modern oil-lubricated wagons with better carrying capacity.

By the time of the Second World War, the average carrying capacity of mineral wagons had risen by 16 tons, but the recent improved overall organization of coal gas and electricity undertakings has made an increase in carrying capacity more economical. British Railways decided, after investigation, to standardize coal wagons at 24½ tons, with a loaded weight of 35 tons. This is the maximum that can be carried on two axles, without introducing restrictions on the route chosen. The standard of 24½ tons produces a better ratio between the pay load and the tare weight. The effect of this is to reduce the amount of train mileage necessary to transport a given quantity of coal.

Larger wagons than these are in use both on British Railways and on railways abroad, but in general the new standard types will be particularly suited to the requirements of British trade and industry.

The most economical wagon for carrying iron ore is one of 25½ tons, when fitted with a bottom-door for discharge, or of 27 tons without doors, when designed to be emptied over the side by a tipping plant. The loaded weight of these wagons is 35 tons.

Under British conditions of trade, the average load of merchandise rarely reaches the average tonnage capacity of a wagon. For this reason, the existing standards of 12 tons for covered wagons, and 13 tons for open wagons, have been retained.

The standard for cattle wagons will be 8 tons, for experience has shown that wagons cannot be loaded with any kind of animal in excess of 8 tons.

A special range of sizes and capacities will be provided for the steel industry, which has particular requirements.

Fruit and banana vans have been standardized, a standard type for the transport of fresh or frozen meat being evolved from the three types formerly in use.

It is found that the annual maintenance costs of wagons made entirely of steel are 12 per cent less than of those made of wood. However, wagons with wooden floors are required for certain types of trade, and consequently these will be retained in a certain number of wagons.

Covered wagons have hitherto been fitted with hinged or sliding doors. The latter have advantages when the wagon is standing at a platform, but are not so easy to open. Hinged or folding doors are being adopted as the standard in future.

In order to protect goods in transit, more open wagons are being fitted with bars for supporting weather sheets, and more are being fitted with shock-absorbing equipment to protect merchandise from being damaged or broken through bumping.

The immense scope of rationalization of railway transport is seen in the development of special containers. These are essentially large boxes which can be packed with particular kinds of goods under the best conditions, and then handled as a whole.

There are furniture containers with a capacity of four tons, fitted with wall battens to which the furniture may be fastened during transit. Four-ton containers for transporting cement, limestone, etc., are fitted with a hatch for loading, and hopper doors for discharging.

Highly insulated containers of 3-ton capacity are used for transporting Dry Ice, i.e. solid carbon dioxide. They are insulated so as to preserve an inside temperature of $-110°$ F.

Four-ton containers are used for transporting meat. These are fitted with hangers, consisting of 8 bars each bearing six single swivel hooks.

Four-ton containers for transporting baths are fitted with rubber cushions to protect the contents during transit.

Two and a half-ton containers are used for packing bricks etc. These can be lifted as a whole by cranes, to the places where they are needed on building sites, or on buildings in course of erection.

Special containers are used for transporting bicycles. These hold 78 machines in two tiers.

The containers can be handled as wholes by cranes mounted on lorries. These are designed to deal with the heaviest containers, and can be run from station to station, where suitable cranes for dealing with heavy containers may not be available. Thus the heavy work is quickly dispatched, and the crane moves on, leaving the lighter freight to be handled with the local equipment.

The handling of freight is greatly accelerated, and the workers assisted, by various forms of special equipment in goods yards and sheds. Portable conveyors are used, the end of which can be put through the door of a wagon, and the cases and sacks inside quickly run out by rolling them onto the conveyor.

Trucks which can be elevated bodily after they have been loaded with merchandise are used for presenting loads of goods at a suitable level for handling.

Mobile cranes with jibs which can enter wagon doors are used for lifting heavy cases. These are driven by electric batteries, and are consequently silent and free from fumes.

Battery-driven handtrucks are being increasingly used, in order to facilitate the handling of goods and parcels.

Tractors are being used instead of shunting engines where this is economical. The tractor has the advantage of being able to run across the rails. Consequently, time is saved in moving it from one place to another, for, unlike an engine, it does not have to follow the rails and pass over various points, etc., to get from one place to another. Some tractors can push up to 200 tons of trucks on straight level sidings.

Horses for shifting single wagons are being replaced by light petrol-driven shunting units which ride on the rail and take part of the weight of the wagon, thus securing sufficient adhesion to push the wagon along the track. Power is provided by a small petrol engine.

RAILWAY SIGNALLING

The fact that hundreds of thousands—nay, millions—of passengers are carried every year by the railways of the world with so few mishaps is a marvellous tribute to the watchfulness of engine-drivers and signalmen. The former may stand on the footplate of an engine for six or seven hours, with very few stops. He has to keep an eye on the pressure-gauge, watch the level of the water, and observe whether the signals at intervals of at most a few miles are for or against him. True, he has a fireman with him, but the driver is responsible, and though the number of matters to which he must give attention has been reduced as far as possible, the speed has to be regulated so that the scheduled time is kept. All this is sufficient by daylight, but when darkness falls there is an additional strain, which is intensified by rain, snow, or fog. In fact, some drivers will not face the responsibility, and decline promotion from the slow goods to fast passenger service.

If the engine-driver must possess clear vision, the signalman must possess a clear head; for he must have in mind all the trains on his section of the line, and send and receive the messages that flash from box to box.

While some accidents arise from defective permanent-way and from negligence, others have their origin in the inevitable fallibility of man. It does not seem to be realized generally that the safety of railway travelling lies in the perfection of the organization—partly human and partly mechanical—that controls the movements of the trains. Men who perform the same series of operations daily, year in and year out, act subconsciously; they discharge their duties with a regularity that is machine-like in its precision. And this action is correct so long as the expected happens. But if the unexpected occurs;—if by some fatal mischance a train which should be in the next section has not entered it, there is an accident. The signalman has learnt by long experience to look, not for the unexpected, but the expected.

Whenever a railway accident occurs from the failure of a man, there is an outcry for the adoption of automatic devices.

Before proceeding to consider some of the plans which have been or are likely to be adopted it will be desirable to consider more exactly the object which it is desired to achieve. At present every railway line is divided into sections or 'blocks' varying in length from one mile to several miles, and the problem is to prevent more than one train being on one section at the same time. This is secured by having a signalman to set the signals at clear, caution, or danger, and an engine-driver to observe them.

Let us consider first the ordinary system of signalling. It may be presumed that everyone is familiar with the way in which a signal arm rises or falls when a lever is moved in the cabin, and knows that the ordinary means by which signal-arm and lever are connected is by long iron rods resting on wheels on short posts. When the signal is a long way off—and the distance must be great for fast traffic—the labour of operating the levers is considerable, and by no system of balance-weights can this be entirely avoided. Some means by which the arm can be raised or lowered is therefore desirable. The 'all-electric', the 'low-pressure pneumatic', and the 'electro-pneumatic' are three of the systems that have been used.

In the first of these the signal-arm is operated by an electro-magnet, the current for which is switched on or off at the signal-cabin.

In low pressure pneumatic signalling the signal-arms are operated by compressed air at 20 lb. per sq. in., and the valves are opened and closed by the usual system of levers and rods.

The electro-pneumatic is the most popular. The air pressure is 65 lb. per sq. in. and the valves are controlled by electricity. The small levers for switching on and off the electric current require less labour and occupy less space than those necessary when the signal-arms and points are operated directly. In the signal-cabin at the Central Station, Newcastle, there are no fewer than 494 levers, and in the cabin of the Central

Station, Glasgow, 374. These figures give some idea of the complexity with which the modern railway engineer has to deal; they also convey some notion of the onerous duties of the man who occupies the box.

In the remainder of this section we shall consider various additional devices which are in operation or have been proposed. Care must be exercised to distinguish between cab-signals and train-stops. Two systems of cab-signals have been in operation in England and are used on all the French railways. But so far train stops have been adopted only on electric railways, and, as we shall see, it is rather in this direction that there is the greatest likelihood of important developments.

A signal may be given in the cab of an engine in three ways; firstly, by means of a trip lever, which stands up between or just outside the rails, and knocks over a lever on the engine as the train passes; secondly, by means of a ramp or sliding contact standing up above the level of the rails and touching a corresponding shoe or wheel on the engine; and thirdly by wireless communication. In all cases a mechanism on the engine is set in motion, and this may drop a small signal, blow a compressed air or steam whistle, light up an electric lamp, or even cut off steam and put on the brakes. Inattention on the part of the driver is in this case of no consequence. He is free to drive his engine, and regulate his speed, with the certainty that if the signals are against him, then snow, or fog, or darkness notwithstanding, he will know of it, and if he does not respond quickly his train may be pulled up for him.

The disadvantage of a trip lever situated near the ground (except in the case of tube railways) is that it is liable to become jammed by snow and ice. Consequently, experiments have been made with a lever mounted on a gallows, and capable of engaging another lever on the roof of the cab. In order to avoid too great rigidity, which is undesirable for high speeds, the upper lever is made to swing, and on a wind-swept piece of line this is again a disadvantage.

Another system involves wireless communication, and is known as the 'railophone'. By the courtesy of International Railophones, Limited, the author is able to give some account of the principles upon which the invention is based. A pair of insulated cables is either laid alongside the line underground or carried on poles, and along these an alternating current is sent. The current produces electro-magnetic waves through which any train on this section of a line must pass. A large coil of wire carried on a frame on the engine or tender serves to collect the waves, and the current produced in it operates a special detector. So long as electric waves are being received the detector keeps a battery on the engine connected up; but immediately the waves cease, the detector stops, the current is cut off, an electro-magnet releases an armature, a small signal in the cab falls, a compressed-air whistle, or electric hooter, or bell sounds, and by suitable devices the steam may be cut off and

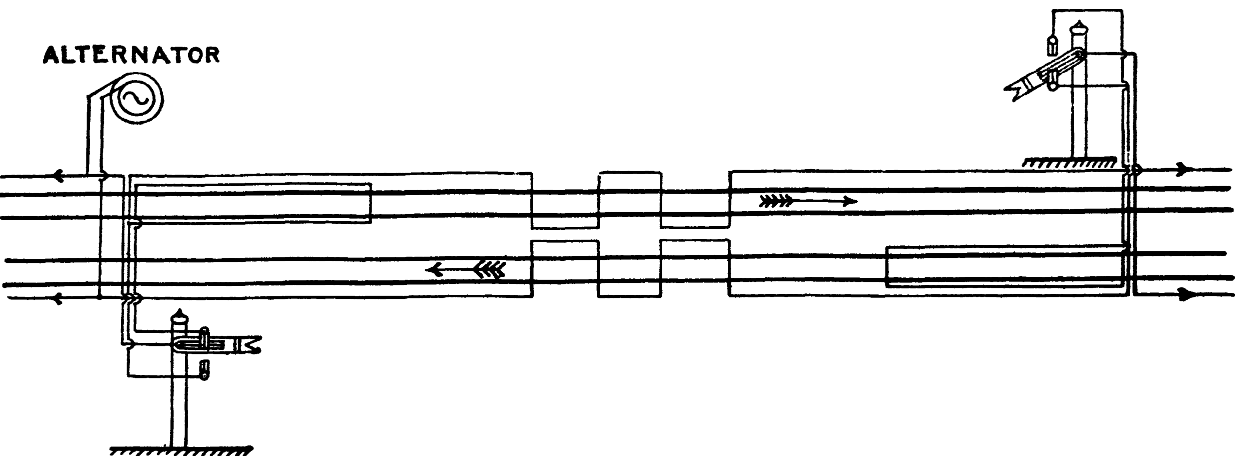


Figure 73. Diagram of connection on line in Railophone system of railway signalling

the brakes applied. The arrangements on the line and on the engine are shown diagrammatically in Figs. 73 and 74.

Temporary interruption of the waves as the train is approaching a distant signal is effected by making what is known as a loop in the line cable. Two of these loops as shown in Fig. 73 will give rise to two short audible signals in the cab of the engine. These are merely to warn the driver that he is approaching the signal. If it is at 'Clear' nothing further happens; but if it is at danger and the driver ignores it, a prolonged audible signal is given, and the steam may be shut off and the brakes applied without further ceremony.

The development of radio has led to the use of the radio telephone in some trains.

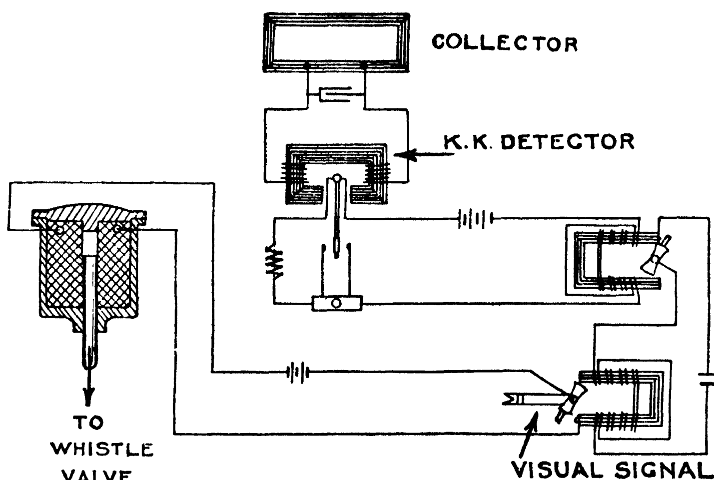


Figure 74. Diagram of connections on engine in Railophone system of railway signalling

In ramp systems the apparatus on the locomotive is put into operation by the contact of a shoe or wheel with the ramp fixed at the side of the line. In this case, of course, no collecting coil or detector is required.

In all these examples the existence of a signalman has been assumed, and the object of the various contrivances has been to draw the driver's attention to the fact that he is approaching a signal, and to prevent him running past a signal standing at danger. A completely automatic system would be created by causing a train standing on a section to connect up an electric circuit and thus set in operation the current in the section behind it.

It will, perhaps, be of interest to describe the method, adopted on the Metropolitan Railway. The system is electro-pneumatic, modified so as

to be automatic so far as the signalman is concerned, except at junctions and points which have to be operated. The arrangement is shown diagrammatically in Fig. 75. A_1, A_2, and A_3 show the successive positions of the same train on the line, and the same letters show the corresponding indications of the signals at the side of the track. One rail is continuous, the separate lengths being metallically 'bonded' together. The other rail is 'broken' about every 300 yards, this distance constituting a section. At the beginning of each of these sections is a signal. The train causes a short circuit in regard to each signal as it passes over the corresponding section, and the signal behind it is raised to danger. No train may therefore enter that section until the one in front has passed out, when the signal falls to the 'line clear' position, and the next one is raised to 'danger'. The frequency with which trains can follow one another is remarkable. At Earl's Court no less than

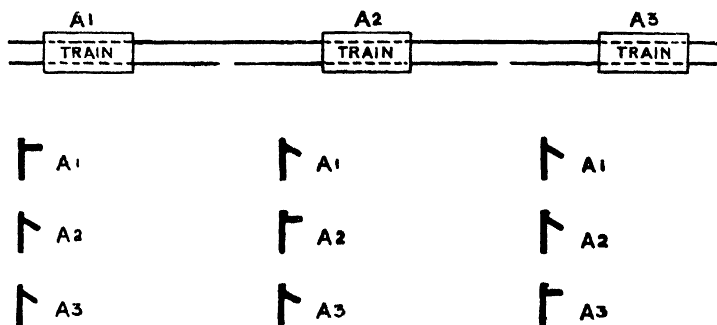
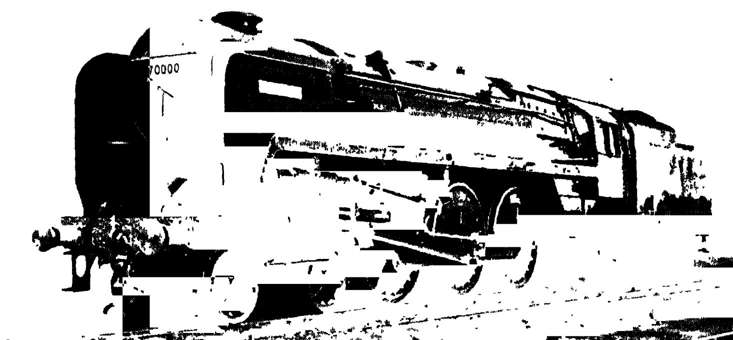


Figure 75. Diagram of Metropolitan system of railway signalling

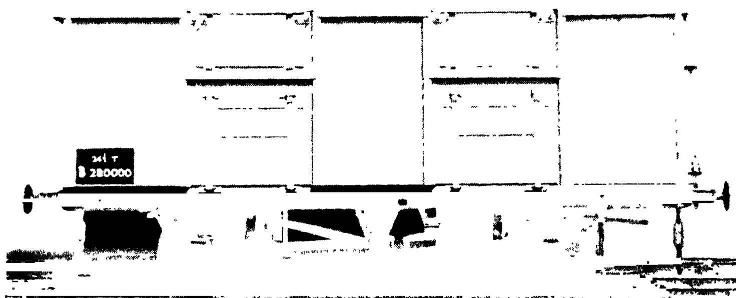
40 trains per hour can pass each way, or a total of 80 trains per hour on two lines.

At junctions automatic working ceases, and the signals are controlled by a signalman. In each cabin is a small cast-iron box with 15 small spaces or windows each 1½ in. square. These have a white background when the line is clear; at other times they show small indicators. On the approach of a train there is a click in the box, and a tablet stating the destination of the train appears in one of the windows. The signalman then presses in a plug and a similar notice appears in the next signal-cabin. As the train passes the first cabin the man presses another plug and the indicator disappears. The progress of the train is therefore notified two cabins ahead, and if the line is not clear the signalman can stop the train.

Another safety precaution is to use steel for the construction of the coaches, and many railways have adopted this plan. Steel has the additional advantage that it does not splinter like timber. At the same time,



XXXVII*a*. No. 70000, British Railways Standard Class 4-6-2 locomotive



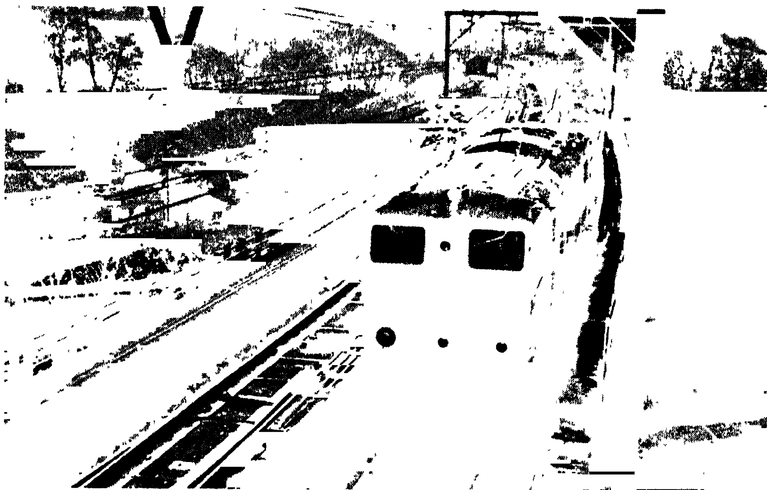
XXXVII*b*. British Railways new standard all-steel 24½ tons flat bottom coal wagon



XXXVII*c*. British Railways standard all-steel coach



xxxviii*a*. A Daimler-Metrovick six-wheeled trolley bus built for the Glasgow Corporation Transport



xxxviii*b*. A 2,490 h.p. 1500 volt 'Metrovick' electric locomotive on the Burnley Line of British Railways, hauling a coal train

it is easier to release an unfortunate passenger from a smashed-up wooden coach than from one of crumpled sheet-steel. The only tool that will cut steel rapidly is the oxyacetylene blowpipe (see Chapter VII) and that cannot be used in very close proximity to a person's body.

The railways are a product of the nineteenth century, and they mark off that period in the world's history more effectively perhaps than any other results of man's handiwork. The material progress that could have been made with the horse-drawn vehicle, or even the cumbrous canal boat, might well have been great, but if these had remained the most effective means of inland communication our population, trade, food, and clothing, and many of our manners and customs would probably be still what they were in 1855.

XIV

ELECTRIC TRACTION

THE first example of electric traction was a miniature railway laid down by Messrs. Siemens and Halske at the Berlin Exhibition of 1879. The method of conveying current to and from the motor is the same as on most electric railways today. A 'third rail' is fixed alongside those upon which the cars run, and the current is collected by a sliding 'shoe' attached to the locomotive or cars. From this shoe it passes to the motor, and back to the generating station through the ordinary rails.

The presence of a 'live rail' close to the ground renders this method unsuitable for use in public streets, and at the Paris Exhibition of 1881 a railway was shown in which the current was conveyed by two overhead wires, from which it was collected by sliders attached to wires leading to the motors. The upper slider was subsequently replaced by a small wheel, and it was also found possible to have one overhead wire and to return the current through the rails. In recounting some of the progress since these pioneer efforts it will be convenient to deal with tramways and railways separately.

TRAMS AND TRAMWAYS

The children and young people of today are hardly able to realize that trams were once small, uncomfortable vehicles drawn by horses, and in a few cases by puffing and snorting steam-engines; and yet it was not until after 1890 that electric tramways began to make any appreciable headway in this country. A few experiments had been made in the 'eighties, such as the lines from Portrush to Giant's Causeway and from Ness to Newry, but these more nearly approached light railways than urban tramways.

The current for a tramway system is generated in a central station and supplied to the overhead wire at a pressure of 500 volts. As the pressure between flow and return tends to become weaker as the distance from the station increases, the wire is usually divided into sections of

about half a mile in length. The reader will probably have noticed at the edge of the footpath near a trolley-wire standard a rectangular metal box or pillar about 3 or 4 ft. high. This is the feeder-pillar containing the switches which enable the current from the line section which starts at that point to be cut out. A glance overhead will reveal two cables running along the bracket and connected with the trolley wires. The trolley wires before and behind this pole belong to different sections.

For very large tramway systems the current is distributed at a pressure of 5,000 volts or more to sub-stations, in which it is transformed to 500 volts pressure for feeding the overhead wire. Whether or not this system is used depends upon the distance and the power to be transmitted. It is often cheaper to erect and equip sub-stations than to put in heavy copper cables over many square miles of country.

It has already been remarked that the most suitable motor for tramway work is a series wound D.C. machine, which gives a strong torque or turning effect on starting. One of these is applied to a front and another to a back axle. The motors are fully enclosed to keep out dust. The axle passes through two holes in the casing at one side of the motor, which is suspended to the frame on the other side by a spring. This permits the toothed wheel on the armature-shaft to gear with a larger wheel on the axle in spite of any jolting due to the unevenness of the road.

The device that usually mystifies young observers is the controller which is fixed in front of the driver and has a handle projecting from the top. Who has not sat at the front end of a car watching the jerky movements of the driver's hand and noting the readiness with which the car responds? The principle and purpose, however, are very simple, though the details of construction are extremely complicated. The first movement of the handle switches on the current, so that it reaches the motor only after passing through a number of wire resistance coils usually placed under the seats. The second movement cuts out one of these coils and allows more current to flow through the motor. The third step cuts out further resistance, and so on until the lever is turned to full speed and the motor receives the full strength of the current. The contacts are inside the controller box, and are separated one from another by sheets of non-conducting and non-inflammable material, so that if, as is quite possible, an arc forms at one contact, the others will be uninjured. A further precaution consists of an electro-magnet which tends to blow out the arc should one be formed. The box also contains a switch for reversing the direction of the current through the motors and therefore the direction of the car.

There are one or two details connected with the overhead wires and the rails which are of some interest. The points at the junction of two overhead lines are sometimes automatic in one direction, but require to

be operated by hand for a car proceeding in the other. It is rather difficult to show this by an illustration, but the reader who desires to understand it should watch the action closely as the trolley passes the points. Again, at the junction of the rails there is a tongue which opens out by the action of the wheels in one direction, but returns after the tram has passed.

The overhead wire and its trolley met with no little opposition in the early days, and much was made of the unsightly character of the equipment.

The rapidity with which electric tramcars can follow one another without confusion is really marvellous, and on some routes a service of a minute and a half is regularly maintained. Under these circumstances delay has to be avoided at all costs, and where no passengers are waiting at the optional stops both power and time can be saved if the driver keeps on. If, however, the conductor is busy collecting fares he is unable to keep that sharp look-out which is essential to quick progress.

A powerful obstacle to the extension of a tramway system to the outskirts of a town before there is a guarantee of regular traffic is the cost of laying the track. This difficulty is being met by the trolley omnibus. This consists of a car constructed after the fashion of a motor-bus, driven by an electric motor, and collecting its current from overhead wires by means of two trolley poles. No rails are necessary, the car is self-steering, and the trolley poles are so mounted that they can swing from side to side of the road without losing contact. The fact that such a car is not confined to rails renders it less of an obstruction than a car travelling on a fixed track, while it is obvious that a greater speed can be obtained. Trams have had to meet severe competition from motor omnibuses, and tramway undertakings are hesitating to renew the track in outlying districts. Buses are quicker, less noisy, and do not obstruct ordinary traffic so much as trams. They involve smaller capital outlay, require less labour, and can adopt any route that may be desirable at a moment's notice. Many tramways are already utilizing them as feeders for, or supplementary to, their existing system. But the capital sunk in tramway undertakings certainly prevents any violent change, and the harsh grinding roar of the trams will still offend the ear in some places.

THE TROLLEYBUS

The tramcar has been widely superseded by the trolleybus. This has the advantages of greater manœuvrability, quietness and cleanliness. In addition, it has the advantage over the bus of using the existing electrical power, which is produced from coal and not from imported oil (Plate XXXVIII*a*).

According to Ministry of Transport regulations, a four-wheeled trolleybus must not weigh more than 12½ tons, and the weight carried by one axle must not exceed 8 tons. The outside width must not exceed 8 ft. A single-decker must not exceed 30 ft. in length, and a double-decker 27 ft. A six-wheeled double-decker must not weigh more than 14½ tons, and the height, unladen, must not exceed 15 ft. 10 in.

Regulations in other countries are somewhat different. The drawing of trailers is not uncommon. In Copenhagen, for instance, trolleybuses and trailers are designed for a combined laden weight of 21 tons.

Typical trolleybus motors develop from 103 to 135 h.p. Their maximum service speed is about 3,250 r.p.m., and they usually run on

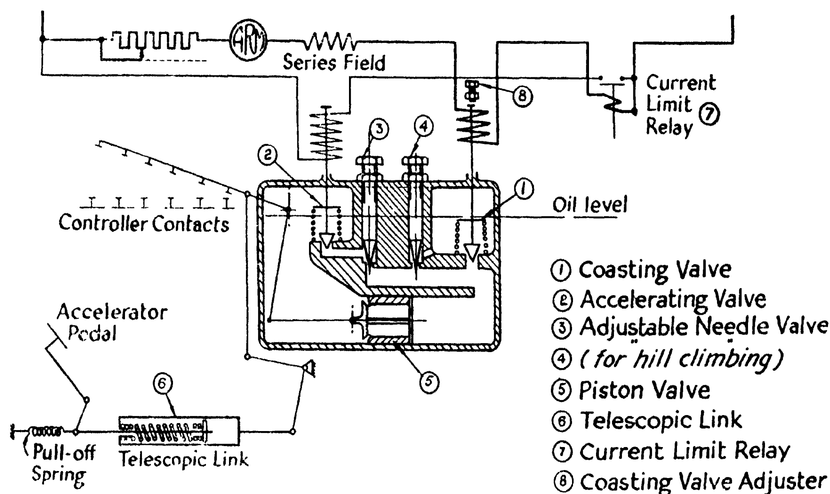


Figure 76. Diagram of the Metrovick automatic acceleration equipment

current at 550 volts. They are designed to have a high power-to-weight ratio by paying special attention to the air-cooling of the field-coils. Special attention is given to the securing of a good commutation system, in order to reduce sparking under the very variable running conditions. It is achieved with the aid of large interpoles, which are unsaturated at the maximum currents used in service, and with the special grading of the yoke sections.

The insulation is very good, in order to withstand the arduous service conditions. Armature and field windings may be insulated exclusively with glass, mica and asbestos materials with heat-resisting varnish.

Metrovick equipment includes a system of automatic acceleration. This operates only when a predetermined rate of acceleration has been exceeded. It relieves the driver of some of his responsibility, and protects

passengers from being thrown about by excessive acceleration. It also protects the motor and transmission from over-stress.

There is provision, too, for a hill-climbing adjustment which prevents the bus from stalling on hills.

The convenience of the trolleybus is much increased by battery-manœuvring. This consists of making use of the accumulator battery for temporarily driving the bus forward or backward, when the trolleys have been pulled off the wires. The battery, normally used for providing current for the lights inside the bus, is divided into halves. These can be connected into series to give the full voltage for driving the traction motor, or in parallel for supplying the lighting and auxiliary circuits.

This manœuvrability enables the vehicle to be driven round traffic obstructions or turned in circles, without dependence on the overhead wires. It removes the necessity for complicated overhead equipment in depots for shunting.

On routes with severe gradients, the bus may be fitted with a special coasting brake. This operates independently of line voltage, and the jumping of the trolley from the wires. It limits the bus to a predetermined speed of 12–15 m.p.h.

An automatic run-back brake may be added, which prevents the vehicle from running backwards on steep hills at more than 3–4 m.p.h.

The switch group in the chassis is at the rear, and can be easily inspected through a panel in the body of the bus.

ELECTRIC RAILWAYS

The growth of enormous towns and groups of towns in close proximity reached such proportions towards the close of last century that the railway engineer found the problems which he had to solve separating into two groups. On the one hand there was the need of a quick suburban and inter-urban service with a fluctuating traffic, and on the other the need for an express service over long distances. The disadvantages of a locomotive and an ordinary train for the former are many, but one is obviously the waste in drawing a heavy engine with a tail of empty carriages during the slack period of the day. It is unnecessary to make more than a passing reference here to the establishment of rail-motor services in which a coach is fitted with a small steam-engine. This serves much the same purpose as the trackless tram already described, and is useful in dealing with traffic along a rural branch line which would not justify a large and heavy train; and it is also used on suburban lines (Plate XXXVIII*b*).

The use of electricity on railways in the early days was delayed to some extent by the notion that cheap water-power was essential and the first electric railways owe their existence to causes altogether outside the

special merits of electric traction. The first real electric railway in Great Britain was the Liverpool Overhead, which runs along the whole length of the docks on an elevated platform. There were clearly objections to an ordinary locomotive 30 ft. above the street level, and the promoters decided to use electricity. Again, the railway under the River Mersey was the first steam railway to be converted to the new method. Difficulties connected with pumping and ventilation, together with the steep gradients at either end, had resulted in lack of financial success, and electricity was adopted as a drastic step—a last desperate effort to convert imminent failure into ultimate success.

About this time the City and South London line was opened. It was the first really deep underground railway in the world, and in it steam was clearly quite out of the question.

Among the chief advantages of electricity in locomotion is the fact that the grip on the rails need not be concentrated at one point, but may be distributed over the train so that the whole weight of the coaches will aid the adhesion of the wheels. Thus two at least of the coaches, and in most cases the first and last, are provided with electric motors, which can all be operated from either end of the train. The electric motor gives rapid acceleration on starting; no shunting is necessary, and when the train is ready for its return journey the driver merely walks down the platform to the other end. No current is consumed when the train is not moving, and coaches can be put on or taken off to meet the variation of traffic.

Many railways use electric locomotives, and some enormously powerful examples of this type have been built. This practice is essential where only a section of a line is electrified. Thus the difficulty of ventilating the great alpine tunnels has led to the use of electricity, and the steam locomotive hands over the train to the electrical locomotive for this part of the journey only. Generally, however, the need for rapid acceleration on starting and the absence of room for shunting lead to the use of motor-cars and trailers on suburban service above or below ground.

Pulling up suddenly and getting up speed rapidly, while achieved more easily by electricity than by any other form of power, throw a heavy strain on the equipment, and an interesting method of reducing it has been adopted on the Central London line. On this line each station is situated at the top of an incline, so that an approaching train slows down naturally on climbing the hill and acquires speed rapidly on descending. This natural method relieves the brakes in the one case and the electrical equipment in the other. But it is obviously not a plan that could be adopted on a line used also for fast through trains.

On a steam locomotive there are always two men, the driver and the fireman, and if one of them is taken ill or dies suddenly the other is able to act in the emergency. But the driver of an electric train is alone. True,

there are conductors, but they are some distance away, the trains follow one another at high speed, and only the driver can see the signals. If anything should happen to him and the current were not shut off, there might be a serious accident. For until the train passed through a station at which it ought to stop there would be nothing to warn the conductors and signalmen that something was amiss, and some little time might elapse, therefore, before the current could be cut off from a section of the line in front of the train. Meanwhile, the cars would be rushing on to destruction with their passengers entirely oblivious of the threatening danger.

Such an event is prevented by a device known as the 'dead man's handle'. On the top of the controller handle, by the movement of which the current is switched on or off, is a small button. Unless this button is pressed the handle cannot be moved from the off position. If by any chance the driver releases the pressure the handle flies back to the off position, and the train comes to a standstill. Moreover, as the signalling arrangements are operated by the train itself the section on which it stands is closed to any train behind it, and an accident is averted.

Before leaving the question of electric traction it is interesting to notice that electricity has in this, as in other cases, created its own demand. The old horse-car could not provide a quicker service than one every fifteen minutes. This is the *slowest* that can be economically provided by electric cars, and in many places a car starts from the terminus every five minutes or even less. Again, on the Inner Circle of the Metropolitan Railway there used to be 16 trains per hour, but with electric traction there are 40. Yet neither bus nor train run empty, and there is if anything a greater struggle for seats than ever there was in the old horse and steam days. In 1908 there were 204 miles of single-track railway worked wholly by electricity in the United Kingdom and 200 miles worked partly by steam and partly by electricity.

What London would do now if compelled to go back half a century in history can hardly be imagined. The 138 miles worked by electricity carried, in 1908, 342,000,000 passengers, or one-third of the total number carried by all the railways of England and Wales in that year. In 1951, London Transport trains ran over 248 miles of electrified track, and carried 623,453,000 passengers. Meanwhile the bus service in London has increased enormously. In 1951, the buses and coaches carried 2,910,444,000 passengers.

Such means of quick transit have an important influence in extending the area of large towns. The country is healthy, and business men will live as far away from the centre of their town as they can cover in, say, an hour's journey. So London and Liverpool by their electric suburban railways, and Manchester and Birmingham by their buses, are spreading out and coalescing with places which were once distinct and isolated.

XV

MOTOR-CARS

ATTEMPTS to drive vehicles on ordinary roads by mechanical power were perhaps earlier than those which led up to the railway, but were far later in coming to a successful issue. When the steam traction-engine made its appearance it was such a clumsy and terrifying contrivance that regulations were laid down to limit its speed, including the requirement that a man carrying a red flag should walk in front to give warning of its approach. During the middle of the nineteenth century many steam carriages of small size were designed, but made no progress, because the weight of the boiler, water supply, and fuel were so great. Not until Daimler, after 1886, had perfected his petrol-motor was there any possibility of rapid development.

Early in the 'nineties this motor had been shown to be peculiarly suitable for propelling a 'horseless carriage', and the result of a number of trials attracted public attention, and gave a great impetus to the industry in France. No headway could be made in England until the 'Red Flag Act' was repealed in 1896. Once, however, this obstacle was removed, the peculiar conditions of Great Britain fostered the use, if not the manufacture, of motor-cars. No country in the world has such a good supply of excellent roads. People were attracted by the novelty and speed of the new mode of locomotion—people who could afford to lay out the money and spend time in mastering the idiosyncrasies of a new and occasionally recalcitrant machine. The demand for private cars and the experience of those who ran them helped in no small measure the improvement which made it possible to use them in the public service and for the purpose of commerce. A brief description of typical engines and of their mode of operation is contained in Chapter IV, and it will merely be necessary now to indicate the chief characters of the essential parts. Thus in addition to the phaeton, there are the torpedo, the limousine, the limousine-landaulette, the coupé-landaulette, the cabriolet, the cabrio-phaeton; and all of these in 'streamline' or other appropriately named forms.

These terms refer only to the upper part or 'body'. The lower part, or frame upon which the body is supported, is called the 'chassis'. It is constructed of steel, generally of channel (⊔) section. In addition there are the engine and its subsidiary contrivances, change-speed gear, driving-gear, and steering-gear.

If the motor-car owes its existence to the petrol-engine, it owes its lightness, speed, strength, and reliability to the new varieties of steel which have been introduced during the last fifty years. If only the older alloys had been available the car would have weighed 20 or 30 per cent more, and a corresponding increase of power would have been required to drive it. Lightness and reliability are due to the use of vanadium steel, which is close-grained, free from cavities, and extremely uniform in composition and texture. It is, however, an expensive material, and the low cost of cars is due to the adoption of mass production. This admits of the extensive use of automatic machines and economy of production. Engines for motor-cars all run at high speed—not less than 1,000 r.p.m.

The noise made by the exhaust gases issuing from an internal-combustion engine render it necessary to use a silencer. This is a long tube pierced with holes and fixed inside one or more tubes similarly pierced. The resistance offered to the successive puffs breaks up the gases and causes them to issue quietly, in a continuous stream. The cylinders must also be cooled by water, and this has to be reduced to the smallest possible amount on account of the weight. After leaving the cylinder jackets the hot water flows through a nest of tubes having thin, waved, metal strips coiled round them on edge. These are placed in front of the car, where the strips, offering a large surface to the air, are quickly cooled. The nest of tubes is called a radiator.

The engine is placed at the front of the car and the driving-wheels grip the road at the rear. Between the head and the tail are a series of mechanisms, the form and construction of which are as important to the smooth running, and other qualities which determine the efficiency of the car, as the engine itself. First and foremost is the clutch, by which the engine is connected or disconnected with the transmission-shaft. This may be of the cone type, but preferably of the multiple plate type. The second mechanism is an arrangement of toothed wheels which enable the speed of the car to be altered. One form depends upon a set of wheels in pairs, one of each pair sliding along a square or 'castellated' shaft. There is a fixed wheel on the engine-shaft which drives a fixed wheel on the short counter-shaft. The counter-shaft has two or three wheels which gear with similar wheels on the transmission shaft. The latter is square or castellated so that it rotates when any one of the wheels is in gear. But by means of forks operated from a lever at the driver's right or left hand, only one wheel can be put into operation at once. As the pairs of wheels—one on the counter-shaft and one on the

transmission-shaft—differ in size, three speeds can be obtained in this way. A fourth—and higher—speed is obtained by coupling the engine-

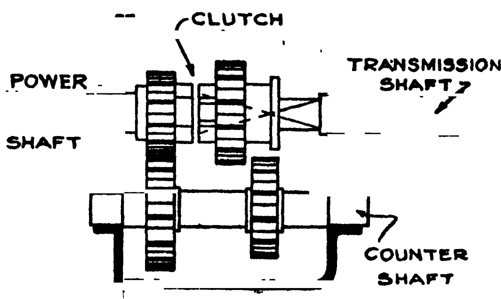


Figure 77. Diagram of simple gear box, giving two speeds

shaft directly to the transmission-shaft. For reversal there must be an extra wheel between the counter and transmission-shafts. This will be clear from a study of the diagram of a simple gear-box, Fig. 77,

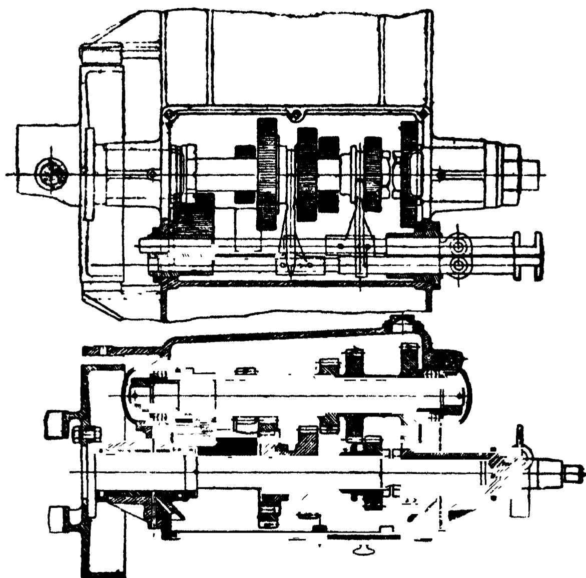


Figure 78. Plan and section of change gearing on the Argyll car

giving only two speeds. A complete gear-box with four speeds and reverse is shown in Fig. 78.

Another form of change gearing is known as an epicyclic train, and is rather difficult for the non-mechanical reader to understand. The accompanying Fig. 79 may, however, help to make the principle clear. A and B are toothed wheels, and the arm C can rotate about the same centre as A. D is a wheel with teeth on the inner side of the rim. If the arm is fixed then the motion of A is transmitted to D through the wheel B, so that D turns more slowly in the opposite direction. If D be clamped and the arm C released, this arm rotates at a rate depending on the sizes of A and B, and in the same direction as A. If both C and D are free, power can only be transmitted through the engine-shaft. This gives two speeds ahead and one backwards, but one of the speeds ahead is that of the engine-shaft. Three sets of wheels like this are therefore necessary to give four speeds ahead and one reverse. The epicyclic train

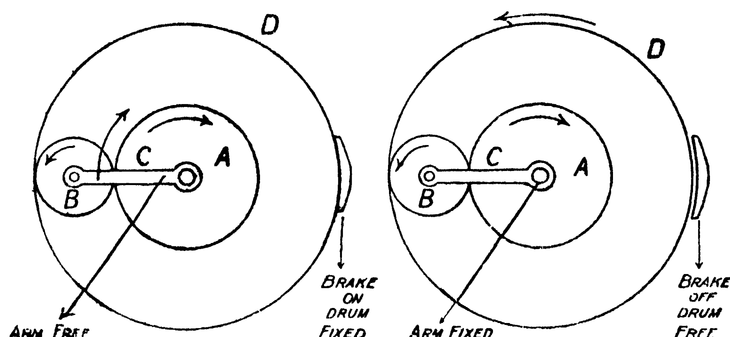


Figure 79. Diagram to explain epicycle change gear

has the advantage of occupying smaller space than ordinary gearing, and as the wheels are always engaged there is no fear of stripping the teeth.

The third mechanism is a flexible joint in the transmission-shaft, between the gear-box and the back axle. The engine and gear-box are fixed to the frame, and the rear axle, being attached by springs, is constantly rising and falling owing to inequalities in the road. A fixed shaft would therefore be bent, or throw undesirable strains on the bearings. The usual form of coupling is a Hooke's joint.

The last step in the transmission of power is the arrangement for communicating the motion to the wheels and is mechanically the most interesting feature of the whole system. The interest arises from the fact that, while both the rear wheels must receive power, they must be capable of rotating at different speeds. For when the car is turning a corner the outside wheel has the greater distance to cover, and if it were not free to turn faster than the other, one of them would have to

slip. The back axle is therefore cut in the middle and the ends are connected through gearing which constitutes the 'live axle' first applied to a full-sized motor-car by F. W. Lanchester in 1896.

Notice first that each half of the axle has a bevel wheel fixed rigidly on the end. Between these two bevel wheels are two or four small bevel wheels in gear with the larger ones. The small wheels have their short axles mounted in a ring (see Fig. 80) or the interior of a circular box, so that the wheels point inward. If this ring or box is rotated then the small wheels carry the larger bevels round with them, and do not themselves rotate, so long as both the large bevels turn at the same rate. But the two bevels are quite free to rotate at different rates, and in that case the small wheels also turn.

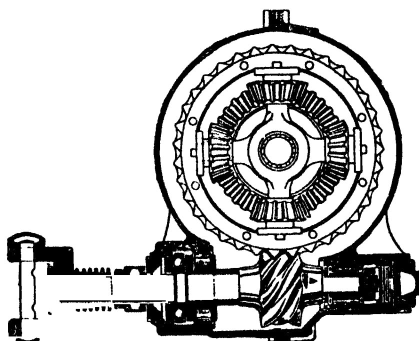


Figure 80. Mechanism of live axle of Lanchester car

The various speeds and the clutch are operated by a lever at the driver's right or left hand, and steering is effected through a wheel in front of him. When this is turned it causes the two front wheels to swing round in the desired direction. These front wheels are mounted upon short axles attached to brackets which are fixed to the end of the front axle by pins about which they are free to turn. The so-called front axle is therefore part of the frame, to which it is attached by springs. The short axles upon which the front wheels are mounted are as a rule not horizontal, but inclined downward. This causes the lower portion of the rim to lie just under the pin about which the wheel is turned when steering. Any other arrangement would cause the wheel to roll forward or drag; it would be harder to work and less sensitive in action.

The brakes are usually operated by a foot-lever, and consist of a broad, flat ring or band of metal like a short drum on each rear wheel. Inside these is a split ring which ordinarily does not touch the outer one, but which is expanded by the movement of the foot-lever. It is usual now for all four wheels to be braked in this way.

On the top of the steering-wheel the reader will have noticed one or two small quadrants with a radial arm or arms. The purpose of one is always to regulate the petrol supply, of the other to regulate the time of the spark. When the engine is running rapidly the time which the mixture of petrol and air takes to burn causes the explosion to lag

behind the piston. The spark is then caused to take place a little earlier, so that the piston receives the full pressure of the burning gases.

The car was originally started by giving a half-turn or so to the engine shaft, but for this purpose the driver has to leave his seat, and this journey round to the front of the car is to be avoided if possible. A very satisfactory starting device is now fitted to cars in connection with the electric-lighting equipment. It consists of a small dynamo driven from the engine and charging a set of accumulators which operate the lamps. To start the car a switch is employed to connect the accumulators up in such a way as to drive the dynamo as a motor, and this drives the engine for a few seconds until the explosions begin.

The modern motor-car is in all cases a comfortable conveyance. Less smooth in movement than the aeroplane, but without the monotonous roll that characterizes a ship, the irregularities of the road are softened and toned down by the most resilient upholstery that man has yet devised. The amount of room in a limousine body is surprising. Here is a complete protection from the weather, warmth, a gentle oscillation, and a gliding panorama of scenery outside the window. A cheap car can only be produced when the pattern is standardized and the whole of the machinery and organization of a large works is concentrated upon its production. The Ford car, first manufactured in America, is a case in point. It was a light car, and English makers preferred at first to turn out a heavier vehicle, which was more durable, and which, they considered, would give the best results in the long run.

English manufacturers, however, gained a vast experience of mass production during the First World War, and afterwards a number of light cars were put on the market. Of these the Morris car was particularly successful. It must be borne in mind that a large number of the cars one sees upon the road are secondhand, and cost their present owners much less than the original price. The extension of motoring is due, in considerable measure, to this transfer from people with more money to those with less.

It has already been remarked that the first use of the motor-car was for pleasure. It was expensive and not very reliable, and possessed many of those qualities upon which the spirit of adventure feeds. The first commercial use was probably made by medical men, who found that speed was of considerable value in enabling a larger practice to be built up without assistance. When a reasonable degree of reliability had been secured, a public service was established first in the form of taxi-cabs, and later by tradesmen's delivery vans. Perhaps no change in the appearance of the streets of large towns has ever been so rapid as that which has resulted in the displacement of the horse.

This enormous traffic has introduced a new problem for the civil engineer. The old macadamized road, which has served the purpose for

100 years, has had its day. Under the endless succession of vehicles that flash from point to point with frequent stoppages, the surface crumbles up, and it has been necessary to use the hardest material, such as broken granite with bitumen or tar to bind the separate fragments together and form an elastic matrix which, by yielding to pressure, reduces wear.

The motor-van or dray is now an essential part of military equipment. No country in the world has such a close network of railways as Great Britain, yet there are many parts specially adapted for military operations which are not readily approached by train. Very stringent regulations as to weight, speed, and hill-climbing power were laid down, and this tended to standardize the type of vehicle used.

The motor-bus is competing severely with trams and trolleybuses, and has established a new network of communications with villages not served by railways.

It is interesting to note that a long time must elapse before competing systems of this kind arrive at a steady state in which one or the other is the victor. The extraordinarily rapid growth of towns during the past fifty years has enabled new forms of mechanical transport to gain a footing without as a rule completely eliminating the old. There has been enough and to spare, for both. The new methods have simply encouraged more people to take advantage of the facilities, and the new supply has created a new demand.

THE SILVER WRAITH

One of the most famous motor-cars is the Rolls-Royce. It has evolved from the prototype created by the engineer F. H. Royce. This remarkable man was born in 1862, in a little village near Peterborough. His father was a miller who died when his son was nine years old. As a boy, Royce had to sell newspapers to help his mother and became a telegraph boy. He already showed mechanical aptitude, and an aunt undertook to pay his apprentice fees to the Great Northern Railway Company. Unfortunately, she died too. Royce tramped for work and found a job with a toolmaker in Leeds. Then he obtained a job in an electrical firm. He spent his evenings in study and making things with a lathe. He worked with extreme concentration and saved a few pounds. At the age of twenty-two, in 1884, he set up an electrical firm in collaboration with a friend, under the name of F. H. Royce & Company in Manchester. The two partners lived in a room over the workshop. They made improved dynamos and small electrical machinery for textile mills, factories and ships, on the principle that the best is the cheapest in the long run, and had considerable success. But the slump following the Boer War struck their business. They were undercut, too, by cheap

machines imported from Germany and America. British industry did not, unfortunately, prove by its actions that it also believed that the best was the cheapest in the end. It already began to show its tendency to buy what was immediately the cheapest.

Royce was quite unable to adjust himself to this point of view. It happened, however, that he bought at about this time a second-hand French Decauville motor-car. He took it to pieces and found a new interest in life studying and adjusting the parts and making new and improved parts with his own hands. In 1903 he began to make an experimental car, which was to be thoroughly silent and reliable. It had a 10-h.p. two-cylinder engine, with overhead inlet valves and an ample water-cooling system. He designed many of the component parts, including the carburettor and ignition system. The clutch was infinitely variable, so that the car made a smooth start. The three-speed gear-box was unusually silent. Every nut and bolt was carefully considered, and even specially made if necessary, in order to reduce rattle and noise. All parts were made as light as possible, and vibration, the cause of rattling, was reduced by careful balancing and springing. The brakes were improved, and the springing was made more generous. By studying the valve-gear and silencer, he suppressed the exhaust noise and valve rattle, caused by the pressure from the combustion explosions in the cylinders.

The car was demonstrated in 1904. One of Royce's fellow-directors, an enthusiastic motorist, recognized the outstanding merits of the new car, and brought it to the notice of the Hon. C. S. Rolls and C. Johnson, who had established a successful firm of motor-dealers in London. Rolls was a famous racing motorist, who had driven French cars, and was looking for an English make. He went to Manchester and tried Royce's car, and at once appreciated its merits.

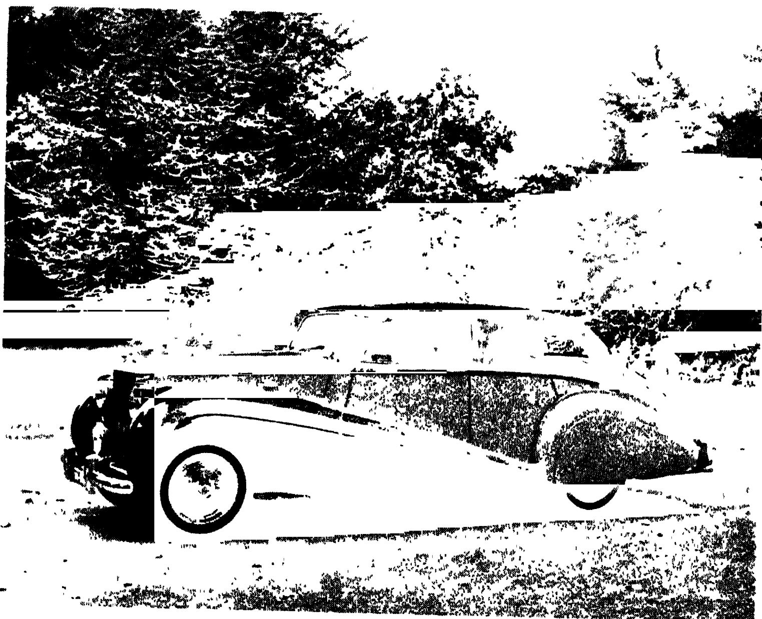
The Times motoring correspondent of the day reported that 'when the engine is running one can neither hear nor feel it, and pedestrians never seemed to hear the car's approach'.

Compared with the spluttering, rattling, roaring cars of 1904, this was indeed extraordinary. The shape of the original square radiator and radiator cap have remained unchanged for nearly fifty years, and are still used in today's 'Silver Wraith'.

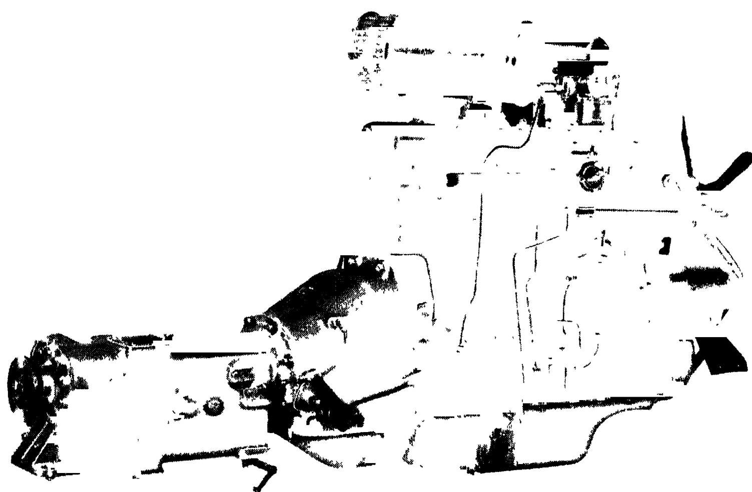
In 1906, Royce produced a six-cylinder car named the 'Silver Ghost', whose main lines remained unchanged for nineteen years.

He made many of the special tools for machining parts to a new order of accuracy, and was prepared to do any job in his works with his own hands.

Presently, the Manchester works was outgrown, and the company selected Derby for the establishment of an entirely new works. Royce superintended every detail of its planning and design. He became com-



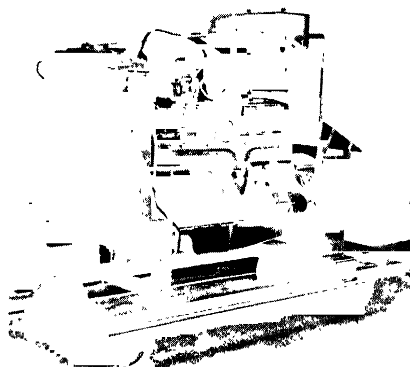
XXXIX*a*. Rolls-Royce 'Silver Wraith', 1952, with coachwork by Park Ward



XXXIX*b*. The Rolls-Royce 'Silver Wraith' engine



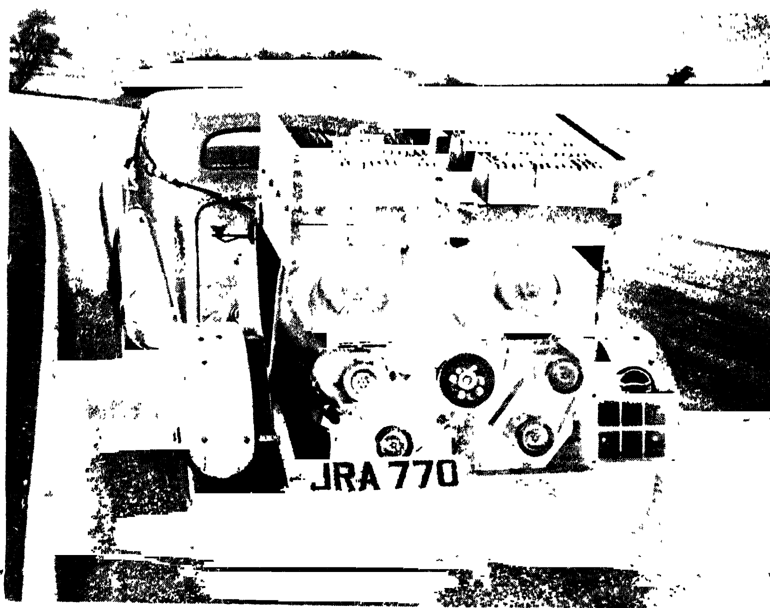
(*Rolls-Royce*)



(*Rolls-Royce*)

XL*a*. Rig for investigating a steering wheel

XL*b*. Engine in rig for cold-warm test



(*Rolls-Royce*)

XL*c*. A trailer made to absorb power in order to test the hauling properties of the car

pletely obsessed with his cars, taking no rest and holidays, and failing to understand colleagues and staff who required them.

He was inclined to diffuse his energy in following too many lines of development. Seeing that his genius was particularly for quality, his colleague Johnson persuaded him to concentrate on one type, and make it the best in the world. Royce and the new works accordingly concentrated on the 40–50 h.p. 'Silver Ghost'.

Then, in 1910, at the age of forty-eight, Royce's health broke down entirely. He had persistently over-worked, neglected his meals, and not taken enough sleep. After convalescing in the South of France he settled in Sussex in 1912. He never went to Derby or saw his works again. But from his Sussex house during the summer and his villa on the French Riviera in the winter, he continued to guide Rolls-Royce design for the next twenty-one years. He always had by him a personal engineering staff, who carried out his suggestions after critical examination of all drawings from Derby. All important cars were brought and demonstrated to him before they were released to the market. Even a severe operation, which left him in need of continuous nursing for the rest of his life, did not stop his unremitting attention.

During the First World War, Rolls-Royce cars were used by the British staff. T. E. Lawrence employed Rolls-Royce armoured cars in his exploits in Arabia. But post-war developments of the car were characteristically slow and conservative. A system of carefully perfected four-wheel brakes operated by a servo-mechanism was adopted. The electric self-starter drove the layshaft in the gear-box through two epicyclic gears. There were other improvements, usually very reliable in operation, but rather complicated in design. By 1924, the car was beginning to look a little old-fashioned. It was replaced by the 'Phantom' in 1925. This had novel features, including a flexible mounting for the engine, which insulated it from the stresses caused by the flexing of the frame. The engine was fitted with two mechanical governors, one controlling the throttle, and the second the advance of the ignition system. There were two ignition systems, one coil and the other magneto. The chance of both breaking down together was very small, and hence ignition failure was virtually eliminated. But the synchronizing of the two systems involved considerable ingenuity.

The Rolls-Royce 'Phantom III', produced in 1935, reflected experience with aero-engine construction. It contained a twelve-cylinder V-engine, with two banks of six cylinders inclined at 60°. The cylinder jackets were cast in one piece, and the cylinder bores formed of iron liners, as in aero-engine practice. Four carburettors were placed in the V.

Lubricating oil was water-cooled and pumped to the crankshaft and connecting rods at a pressure of 50 lb. per sq. in., to the valve-gear at 10 lb., and to the timing gear at 1¼ lb.

Noise in the valves was eliminated by a hydraulic device in each valve rocker, which automatically maintained a fine clearance in the valve mechanism.

The most striking innovation in the chassis was the use of independent suspension for each of the two front wheels.

In the 'Silver Wraith' of 1952, a six-cylinder engine of bore $3\frac{5}{8}$ in. and stroke $4\frac{1}{2}$ in. is installed. It has a capacity of 4,566 c.c. and is rated at 31·5 h.p. The cylinder block is in one piece with the crank-case, and has an aluminium head. The top $2\frac{1}{2}$ in. of cylinder bore are strengthened with a tough chromium-iron alloy to resist wear. The exhaust valves are side-operated, which allows deep breathing of the engine through the inlet valves. The carburettor mixture is automatically controlled by a bi-metallic strip (Plate XXXIX*a*).

This ensures easy starting when the engine is cold, and flexibility over the whole speed range. A silencer and filter are attached to the air intake. The temperature of the coolant in the cooling system is controlled by thermostatically-operated radiator shutters.

The gear-box contains four speeds and reverse, and the clutch is of the dry-plate type. The engine and gear-box are in one unit, and mounted on rubber. They are fixed so as to allow of torsional flexibility, and thus protecting the passengers from engine vibration. The interior of the car is insulated from minor noises and road vibrations (Plate XXXIX*b*).

The propeller shaft has three universal joints, which give the car a low and flat rear floor. The centre bearing is insulated so that shaft vibrations are not transmitted to the body.

Each front wheel is independently slung on helical springs controlled by hydraulic dampers. The rear suspension is on semi-elliptic leaf springs combined with hydraulic dampers. These consist of a piston pushing oil through a valve in a cylinder. The degree of damping can be regulated by the driver, according to the speed of the car, by a lever on the steering column.

The rear road springs are carefully ground to size and fit. The leaves are cadmium-plated to obviate wear and squeaks. The springs as a whole are encased in leather garters and contain a self-lubricating arrangement.

The front brakes are hydraulically operated and the rear brakes mechanically. A servo-mechanism increases the pressure on both systems, so that adequate braking is given with minimum physical effort by the driver.

The windscreen is freed from mist and frost by hot air from the radiator. Air is warmed by a water-heater under the front passenger's seat, and conveyed through ducts to the front and rear compartments of the car, in order to provide comfortable conditions. A six-valve radio receiver is included in the fittings.

In order to produce such refined machines, an immense amount of research and testing is necessary. The Rolls-Royce Company expect every component of their cars to run 250,000 miles under the most severe conditions without failing. In order to achieve this, test-rigs are devised which will submit the component in the laboratory to the kind of strains it will receive in use.

A gear-box and transmission set is driven by an engine or electric motor for long periods, in order to test the properties of the system. An engine without pistons is run in order to study the operation of the valves at high speeds.

Wheels and their tyres are tested on drums, to discover their slipping and skidding properties. It was found that at low speeds wheels do not bounce vertically over lumpy objects, but at high speeds they do. The reverse happens in running over hollows. With this apparatus the magnitude of the side-load at which the tyre begins to squeal can be determined.

The heaviest stresses on the steering gear, which are studied by the rig shown in Plate XL*a*, are not developed when the car is going at high speed, but when it is parking, and manœuvring at low speed. In the rig, the column can be twisted backwards and forwards automatically until it breaks down.

The leaf spring is subjected to oscillations produced by a crank. The deflection is recorded by instruments, and the apparatus runs until the spring breaks down.

The properties of radiators are investigated by an 'iron lung' which breathes heavily into a water-filled radiator, in order to discover the effects of cyclic changes in pressure and weaknesses in the radiator construction.

A rig is used for testing every feature of the water circulation system.

In order to study the behaviour of the engine in hot or cold climates, a rig is used for testing it in a cold room (Plate XL*b*).

Even the properties of tool-bags are tested. How long will tools be held by their clips, through the shaking of the car? Tool-clips are shaken in a rig to find out.

In order to study the behaviour of the car on the road, a trailer containing various kinds of apparatus is towed. It contains electrical resistances which act as brakes of exactly known power on the trailer. The reaction of the car to this drag can then be investigated (Plate XL*c*).

The trailer will absorb up to 100 h.p. When the car is run under these conditions, they approximate to the running of the car at full-throttle but low speed. This enables the transmission, vibration, and cooling to be submitted to severe tests.

The great refinement of design has been paralleled by the rationalization of production methods. Many of the parts of Rolls-Royce engines

are made to standard sizes. Consequently, engines of different types for varying purposes can be assembled from the same range of basic parts. Thus, from this small range, engines for six-wheel army trucks, fire engines, reconnaissance cars, industrial lorries, and luxury cars, can be assembled with slight modifications. The whole engine production can be turned, almost at will, from industrial to military purposes (Plate XLI*a*).

The number of spares necessary for repairing the range of vehicles used in World War II was about 3,000. If the Rolls-Royce 'B' series of machines had existed to provide the equivalent transport, only about 300 would have been necessary.

XVI

SHIPS

PROBABLY no field of invention has been more startling in its results than that connected with ocean transport. The old vessels in which the adventurous spirits of the sixteenth and seventeenth centuries sallied forth across the waste of waters and founded the British Empire, possess only a superficial resemblance to the magnificent vessels of the present day. And when one looks at the comfort and convenience of the modern steamer the imagination is exercised to picture the daring and hardihood that planned and executed those early voyages. In the volume dealing with the nineteenth century an account is given of the advent of the iron and steel ship, of the growth in power and speed which had taken place by 1890. It may safely be said that the progress during the past fifty years has been as remarkable as anything that preceded it. At the same time, there is probably a good deal of popular misconception in regard to size. The newspapers have dealt so generously with the giants *Queen Mary* and *Queen Elizabeth* that these huge liners are regarded as representative. But as a matter of fact, they are only engaged in the Atlantic trade. They owe their existence to, and represent in full measure, the commercial interests existing between Europe and America.

Thus, in 1912, if steamers of less than 500 tons are excluded, the average size of the ships launched in Great Britain was 4,000 tons. Only 16 vessels were over 10,000 tons, and 54 were between 6,000 and 10,000 tons. The general cargo boat is not as a rule more than 6,000 tons, because beyond this size difficulties arise in making up and breaking cargo.

CONSTRUCTION

The problem of constructing a ship of adequate strength is a very interesting one. The chief forces that have to be considered in an ocean-going boat are those which arise from the uneven surface of the water. Fig. 81 shows how at one moment she may be supported at both ends

on the crests of two waves, and at another supported in the middle on the crest of one wave, with both ends free. In both cases the forces called into play are the same as those in a beam supported in a similar

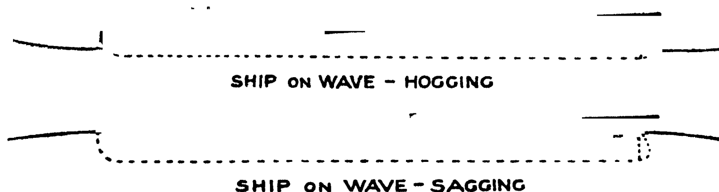


Figure 81. The need for longitudinal strength

way. And it is clear that a form of construction similar to that of a box-girder is essential. The effect is obviously more serious as the length of the ship increases.

The old wooden ship was of no great length, and no great strength was required in a longitudinal direction. All the heavy timbering was concentrated in the ribs running from deck to keel. If she was strong enough to escape being battered in, her bottom, sides, and deck were strong enough to prevent her back being broken. But the advent of iron and steel ships brought a great increase of length, particularly when it was found that an increase in carrying power could be effected in this way without a corresponding increase in the horse-power required. As the length increased the transverse system became no longer permissible, and methods were devised by Scott-Russell and others to stiffen the frame in a longitudinal direction.

There is a very general tendency nowadays to look closely into the quantity and distribution of the metal in the hull, and it is quite possible that a considerable saving of weight will be effected, and result in a corresponding increase of carrying capacity. The shipbuilder benefits by the improvements in the manufacture of steel described in Chapter VIII. Not only is the material more reliable, but it is supplied in larger pieces, so that the amount of labour involved is less. When the *Great Eastern* was built in 1858 the plates used in her 'skin' were 10 ft. long and 2 ft. 9 in. wide; the plates used on a large modern vessel are 30 ft. long and 5 ft. wide. The area of the old plate was therefore 27½ sq. ft.; of the modern one 150 sq. ft.

SPEED

Another feature in which the giant liners are not representative is the speed. The usual speed of a cargo boat is 10 to 12 knots. The *Mauretania*, launched in 1907, held the record for twenty-two years. The expense of attaining the extra knots is so great that no company, unless

heavily subsidized, would find it worth their while to undertake it. The money for this ship was advanced by the Government, and an annual sum paid for its upkeep. In return for this the Government had the right to its use in time of war. The ship carried two guns, and was specially strengthened for this purpose.

The practice of stating the speed of a ship in knots is somewhat confusing to a landsman, who often fails to realize exactly what the figures mean. A knot is 6,080 ft., and that is nearly $1\frac{1}{5}$ land miles. A speed, then, of 20 knots is, in terms which the landsman understands, a speed of 24 miles an hour, and the *Queen Elizabeth* travels at 35 miles an hour. On many sections of British railways the speed does not exceed this figure. The reader who has not reflected upon this matter before should estimate the velocity of the train on his next railway journey, and notice how the trees and hedgerows appear to fly past. He can then imagine a ship like the *Queen Elizabeth* racing through the waves hour after hour with never a stop for four days and four nights until she comes in sight of land. It will be possible, too, to realize how little time there is in which to avoid a collision. The *Queen Elizabeth* covers a mile in less than two minutes. A ship or an iceberg sighted five miles away is reached in ten minutes, and a vessel of this size cannot be reversed in a hurry without fear of damage to her engines.

In order to secure speed with a minimum of power it is important that a ship should have such an outline as will enable her to move through the water with the least resistance, and the power required to drive a vessel of given displacement and form at any particular speed can be determined beforehand with considerable accuracy.

It will perhaps assist the reader to realize the kind of movement that goes on when a stream of fluid meets an obstacle if a short description is given of the method of study devised by H. S. Hele-Shaw. In his experiments alternate holes in the end of a small glass tank are fed with coloured and uncoloured glycerine and produce a series of parallel bands. If an obstacle, in this case representing a ship's rudder, is placed in their path these bands divide and curve round its surface, as shown in Plate XLII*d*, which is from a photograph shown by Hele-Shaw at the Institution of Naval Architects in 1900. It was found that in a few cases in which calculation was possible, the stream lines corresponded exactly in form to those which would be produced in a perfect fluid.

Water, however, is not viscous—at any rate in comparison with glycerine. Moreover, a thin film can only represent the influence on a floating body at a particular depth, and the speed of a vessel is usually greater than that at which the glycerine experiment fulfils the ideal conditions. Another illustration (Plate XLI*b*) exhibited by Hele-Shaw will make the problem clearer. The liquid used in this case was water, and the thickness of the film was increased. The stream lines in front of

the obstacle were replaced by sinuous motion, and the space behind was filled with 'dead water' and eddies, in which all steadiness of motion disappeared.

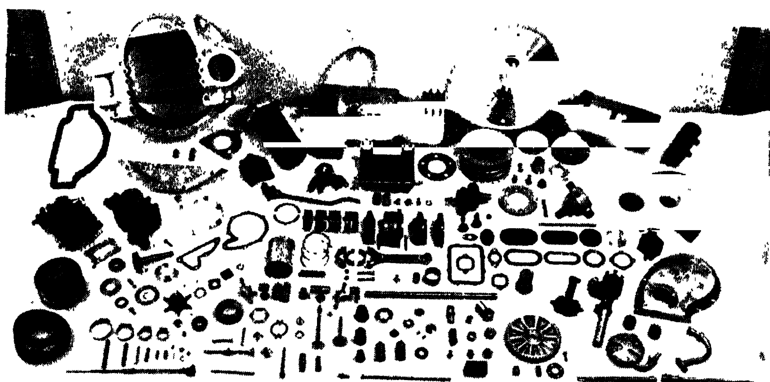
The object of having a sharp prow is to effect the gradual displacement sideways of the water. But it is equally important to provide a sharp stern. For the stream lines tend to close in gradually as the ship moves; and a blunt stern would tend to cause cavities behind, which would act as a drag on the ship's progress. These facts are well illustrated in Plates XLII*a*, *b*, and *c*. In a screw steamer there is an additional reason for this form of construction. The propellers are continually forcing the water backwards, and unless it can flow in freely in front of them the maximum push on the water cannot be obtained. A blunt stern would act as a shield.

When a vessel is to be constructed the purchaser stipulates a certain tonnage and speed; and the shipbuilder must decide what horse-power will be necessary to attain this. But the power required will depend very considerably upon the 'lines'—that is upon the change of shape of the submerged portion from stem to stern. And though experience allows a very good result to be achieved, there is a method which enables the best lines to be determined, and the necessary power to be ascertained, with great accuracy.

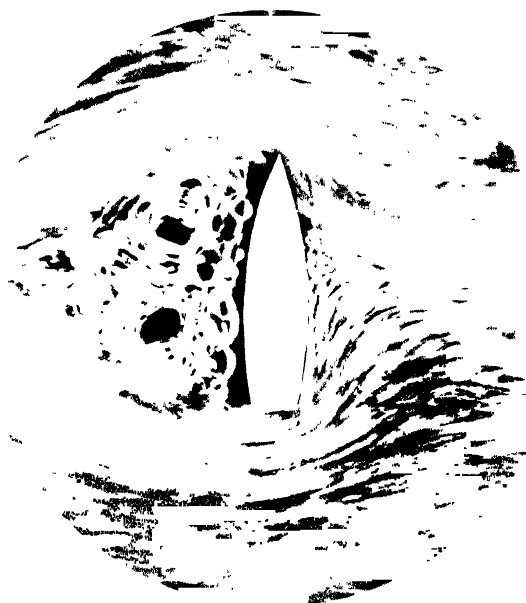
It was in 1871 that the late William Froude designed for the Admiralty, at Torquay, a long tank in which scale models of ships could be towed and the power required for any given speed could be measured. Between the size, power, and speed of the model, and the size, power, and speed of a large vessel of the same shape, there is a definite relation, which enables the naval architect to draw his plans with the certainty that the result will be satisfactory.

The William Froude National Tank at the National Physical Laboratory, which owes its origin to the generosity of A. F. Yarrow, is built of concrete, and is 550 ft. long, 30 ft. wide, and 12½ ft. deep. These dimensions, with the models used, are equivalent to open water for a large ship. A false bottom can be put in so as to permit of trials in shallow water. It is spanned by a bridge running on rails and driven by four electric motors. This bridge serves to tow the models, and is equipped with delicate measuring instruments for recording the pull and speed. These arrangements are shown in Plate XLIV*a*.

The models are made in paraffin wax, from 12 to 20 ft. long, with sides and bottom about two inches in thickness. They are cut out in a sort of milling machine in which the cutter is actuated in accordance with the motion of a pointer, which is made to travel along the lines of the drawing, which rests on a table at the side of the machine (Plate XLIV*b*). The tool thus shapes the wax to the exact form intended by the designer. The marks of the cutter are removed by scraping so as to



XLI*a*. Common parts for Rolls-Royce engines of 4, 6 and 8 cylinders developing between 80 and 160 h.p.



XLI*b*. Sinuous flow in water showing eddies behind an obstacle

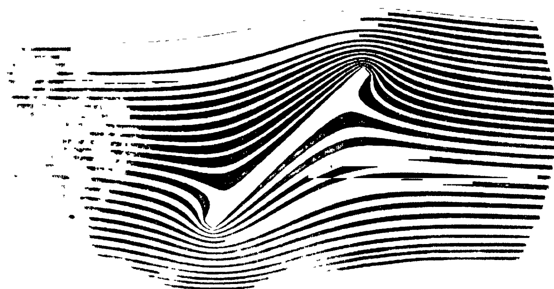




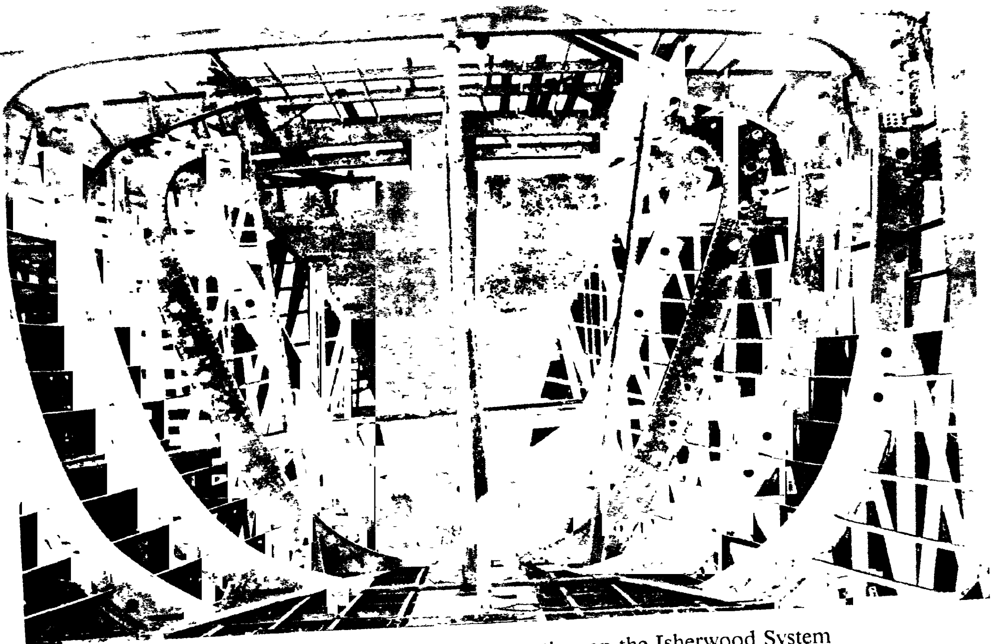
XLII*a*. Sinuous flow in water showing a relatively small importance in a ship of a blunt bow in producing eddies

XLII*b*. The influence of a blunt stern in producing eddies

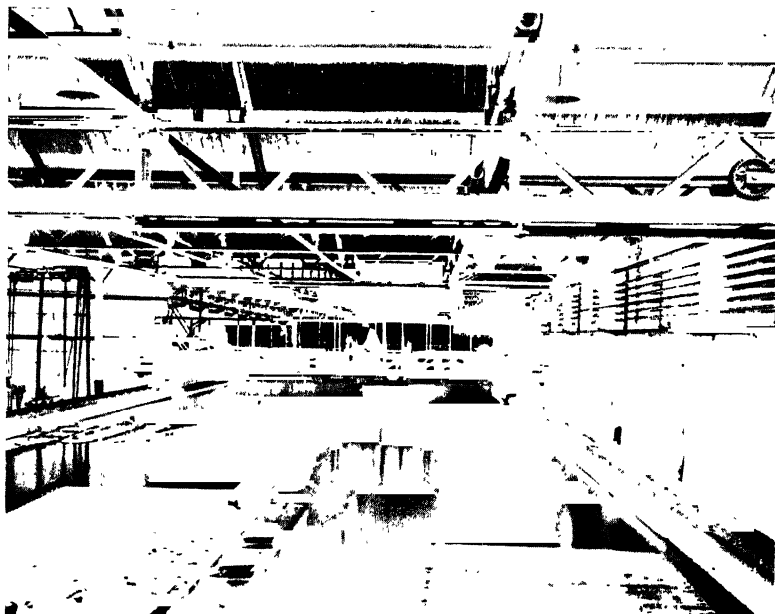
XLII*c*. How eddies are avoided by giving a ship fine lines fore and aft (flow is from left to right)



XLII*d*. Stream lines in glycerine passing round an obstacle

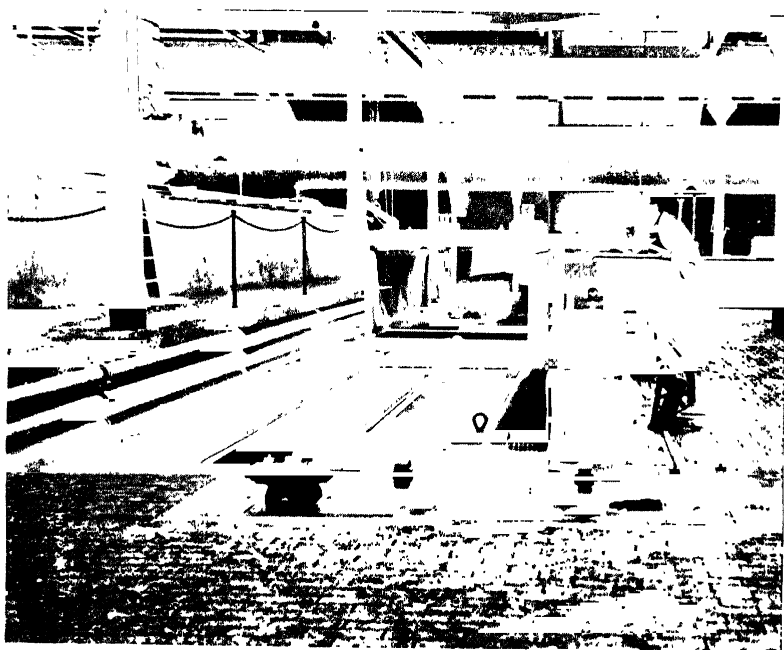


XLIII. A ship in course of construction on the Isherwood System



(*National Physical Laboratory*)

XLIV*a*. The William Froude Memorial Tank; model ready to be towed



produce a smooth body, and ballast is then added until the model floats at the required depth.

The installation of the National Physical Laboratory tank has enabled many shipbuilders to adopt the precaution of checking the design of cargo boats, and every kind of smaller craft. In 1920 more than two-thirds of the designs submitted for tests had been improved by at least 2 per cent. In the 23 test examples the average reduction of indicated horsepower at service speed has been 8½ per cent. Assuming that only one ship is built to each of these 23 designs, the net saving of coal per year for the 23 ships amounts to 15,000 tons, on a basis of 200 steaming days per year.

SAFETY

Safety at sea is secured partly in the construction of the ship, and partly by the use of subsidiary appliances. Thus the vessel is divided into a number of watertight compartments separated by partitions or bulkheads, and covered by a watertight steel deck. Communication from one compartment to another and through the deck is obtained by sliding doors which fit in watertight grooves. These can all be closed when necessary from the bridge. They are operated by hydraulic pressure, and the force is so great that any obstruction, such as a lump of coal, is cut through during the closure. The control is fixed on the bridge, and immediately behind the lever which operates the doors is a model of the ship with an electric lamp corresponding to the position of each compartment. Should one of the doors fail to act when the lever is set to close a lamp lights up corresponding to the compartment with the open door.

It has generally been assumed that a modern ship will continue to float with any two of her compartments full of water, but the naval architect now makes assurance doubly sure. The *Olympic* was provided with a complete inner skin. Plate XLV*a* shows the inner skin of the *Olympic* being fitted as an additional precaution after one or two voyages had been made.

But if a ship runs full tilt against an obstruction big enough to stop her, no system of stiffening, or bulkheads, or inner skins can prevent her crumpling up like a paper bag. When one compares the thickness of the skin and longitudinal bulkheads with the whole width of beam, it is clear that the great ship is a frail thing indeed, and no precaution that will keep her clear of icebergs or a rockbound coast can be safely neglected. During the last thirty years an 'ice-scout' has been employed to watch the movements of ice in the North Atlantic and to report its presence and position to all ships on the track.

Sometimes the course of a vessel has been altered, and a ship has

been wrecked when the captain believed himself to be clear of any rock or coast. The recording compass enables him to ascertain whether such an alteration has taken place. It consists of a roll of paper on a rotating clockwork drum, upon which a line is traced by a pen. If the course of the ship alters the change in direction and the exact time at which this took place are indicated by a bend in the line on the paper.

An additional method of avoiding dangerous coasts has been introduced by submarine signalling. Ever since the famous experiments of Colladon and Sturm on the Lake of Geneva in 1826 it has been known that sound travels through water with a velocity four times greater than through air.

ECHO SOUNDING

The use of echoes for determining the depth of the sea, for locating icebergs and under-water obstacles, even enemy submarines and fish shoals, has been greatly developed during the twentieth century. It is a new aid to safety in navigation and success in fishing.

The principle is simple. A sound-producing device sends short claps or pulses of sound from the bottom of the ship. These are reflected from the bottom of the sea, or from any object which is to be located, and the time taken for the sound to travel from the sea bottom back to the ship is measured. As the velocity of sound in water is known, the depth of the bottom, or the distance of the shoal of fish, or a submarine, can be calculated. This is done automatically by a machine, which draws a graph revealing the depth or distance at a glance.

The use of sound-waves for location by echo has been used by man for finding his way in caves and mountains. The most extraordinary case of this phenomenon being utilized in nature is, however, in the

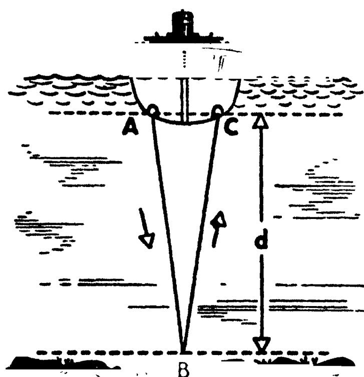


Figure 82. The principle of the Hughes echo-sounder

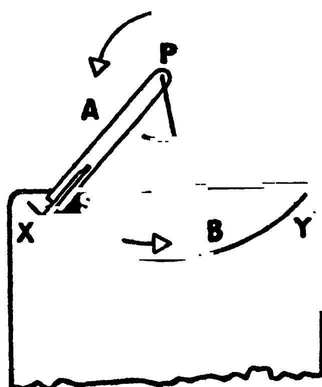


Figure 83. The chronograph of the echo-sounder

steering mechanism of the bat. This animal flies blind in the dark. It emits sounds or ultra-sounds of very high pitch. Its hearing mechanism automatically tells the distance of objects into which it might fly, from the time taken for the echoes to come back to the flying animal.

Sound-waves travel in water at a velocity of 4,800 ft., or 800 fathoms, per second. The basic scheme is shown diagrammatically in Fig. 82.

If the sound takes one minute to travel from A to B, and B to C, then it follows that the depth of the bottom will be about one-half of 800 fathoms, i.e. 400 fathoms. If the depth is only 20 fathoms, then the time taken will be $\frac{1}{20}$ of a second, etc.

An accurate chronograph is needed to measure these small intervals of time. The principle of this is illustrated in Fig. 83.

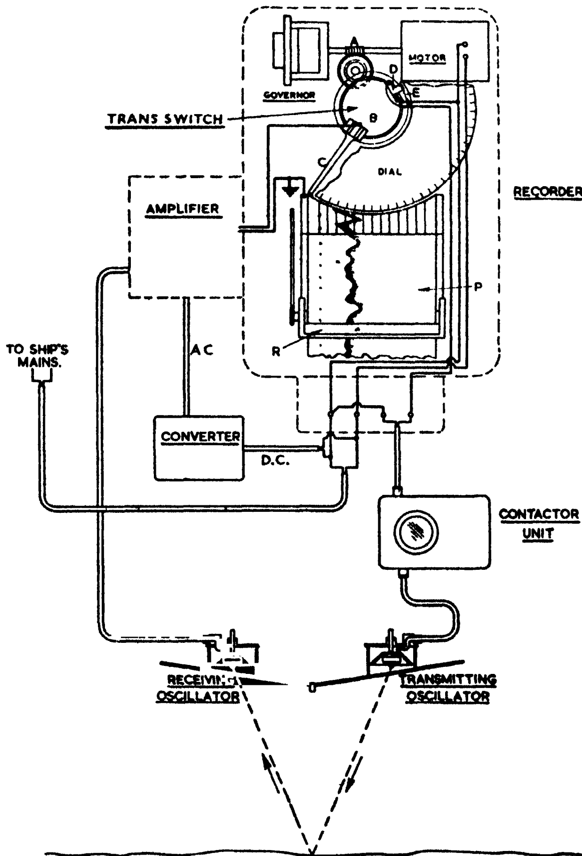


Figure 84. Schematic diagram of the recording echo-sounder

An arm A rotates at constant speed around an axis P, in an anti-clockwise direction. A pen is attached to the end of the arm and traces an arc XY as it travels over the recording paper. Every time the pen passes X it operates a switch which causes a pulse of sound-waves to be emitted. By the time the echo has returned, the pen will have reached

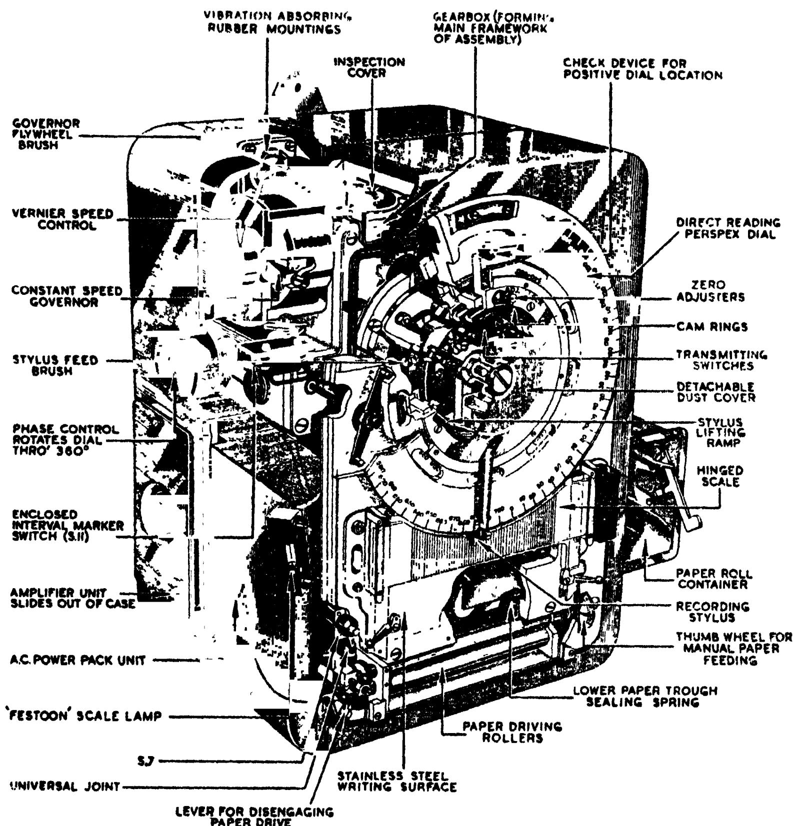


Figure 85. A general view of the recorder unit

the point B. The distance XB, or the angle XPB, can be used as a measure of the time taken by the sound to go and return, as the rate of revolution of the arm is known.

In the Kelvin-Hughes echo-Sounder, the sound is emitted by an oscillator working on the magneto-striction principle. This is the phenomenon shown by certain metals, especially nickel, which expand or contract when placed in a varying magnetic field. A nickel structure

is placed within a coil. A surge of oscillating current through the coil produces a high-pitched sound, audible to persons with good hearing.

The sound-waves produced by the oscillator are focussed by a conical reflector and projected downwards through the ship's hull. The echo is picked up by a receiving nickel oscillator, which produces a corresponding oscillator current when the echo falls on it. An amplifier multiplies the current about two million times, and enables the time of arrival to be recorded by the pen. The general arrangement of the system is shown diagrammatically in Fig. 84.

A general view of the recorder unit is seen in Fig. 85.

A reproduction of an echo-sounder chart, on which the position of a herring shoal is revealed for the aid of fishermen in a herring boat, is seen in Plate XLV*b*.

The echo-sounder not only locates shoals of fish. It can give a continuous portrayal of the profile of the sea bed which is being trawled, enabling the fisherman to avoid obstacles which might damage his nets and tackle. Favourite fishing banks are located quickly, which is a great aid especially in foggy weather. The echo-sounder is revealing more exact information of where the fish congregate near a bank or ridge. This enables the fisherman to put his nets more exactly where the fish are. In Norway, already, fishermen do not shoot their nets until the sounder shows a sufficient density of fish at a suitable depth.

The fish of the sea are a food resource which is as yet very partially developed. The application of the echo-sounder and other scientific devices will enable the world's food resources of valuable fish proteins and oils to be greatly increased.

THE BIGGEST SHIP

Up to the 1930's, three liners were necessary to conduct a weekly service both ways between Southampton and New York, because existing vessels were not fast enough to make the voyage and complete the reloading and turn-round within seven days. The Cunard Line conceived the project of building two ships fast enough to perform the voyage and turn round, and big enough to carry as much passenger traffic as three of the older big ships.

The first of the two ships in the realization of this project was the *Queen Mary*. The contract for the construction was placed in December 1930, and the ship was launched in September 1934. She made her maiden voyage from Southampton to New York in May 1936.

The *Queen Mary* is 1,019 ft. long, 118 ft. broad, and 92½ ft. deep. The height from keel to superstructure is 124 ft., to the top of the

forward funnel 181 ft., and to the top of the masts 237 ft. The draught is 38 ft. 10½ in. The gross tonnage is 81,237.

She became the fastest liner of the day by steaming from Bishop's Rock to the Ambrose Lightship in 3 days 21 hours 48 minutes, and returning in 3 days 20 hours, 42 minutes, the respective average speeds being 30·99 knots and 31·69 knots. The record stood until July 1952, when the American liner *United States* on her maiden voyage steamed East to West in 3 days 10 hours 40 minutes at an average speed of 35·59 knots, and returning in 3 days 12 hours 12 minutes at an average speed of 34·51 knots.

The *Queen Mary* left Southampton on a voyage to New York in September 1939, finding on her arrival there that the Second World War had begun. She was laid up there during the winter of 1939, and then in March 1940 sailed for Sydney, Australia, to begin troop-carrying, and to carry out, presently in co-operation with the *Queen Elizabeth*, the sister-ship in the Cunard Company's two-ship Atlantic project, a unique and astonishing achievement in military transport during the remainder of the war.

The keel of the *Queen Elizabeth* was laid in December 1936. The ship was launched in 1938. Her maiden voyage was made in secret from the Clyde to New York in March 1940. Her first commercial voyage was made in October 1946, from Southampton to New York (Plate XLVI*a*).

She is 1,031 ft. long, her breadth is 118 ft., and height from keel to superstructure 135 ft., to top of forward funnel 180 ft., and to masthead 234 ft. The draught is 39 ft. ½ in. The gross tonnage is 83,673. She has 14 decks. The promenade deck is 724 ft. long. There is accommodation for 822 first class, 668 cabin and 798 tourist passengers. The crew numbers 1,280. The cargo space is 46,295 cubic ft. and 14,465 cubic ft. insulated for refrigeration or constant temperature.

The *Queen Elizabeth* has three radar units, one with a range of fifty miles, another with a range of ten miles, and another for detecting aircraft. Her rudder weighs 140 tons. It is streamlined with the rest of the hull, and doors in the side allow it to be inspected from the inside, when the ship is in dry-dock.

She has three anchors, each weighing about 16 tons. These are held by 990 ft. of chain cable. The links in the chain are each two feet in length and their total weight is 225 tons.

Twenty-six steel lifeboats are carried. Each is fitted with high speed diesel engines, and can carry 145 passengers. A fully-loaded boat can be lowered in a few seconds by one man.

Each letter in the name of the ship painted on the bows is 2½ ft. high, and the whole name is 68 ft. long.

The amount of metal in the hull and machinery exceeds 50,000 tons. There are 140 watertight compartments in the hull. The steel plates

of the hull are from 8 to 30 ft. long. More than ten million rivets were used in putting the hull together.

There are 2,000 windows and portholes in the steel structure. The ship has 35 public rooms, a cinema seating 338, two swimming pools, and three libraries containing more than 4,000 books.

The main engines develop 160,000 h.p. They consist of four sets of single-reduction geared turbines driving four propellers, each of which weighs 32 tons, and has a diameter of 18 ft. There are 257,000 blades in the turbines. Steam is supplied from twelve boilers to the main engines, at a pressure of 425 lb. per sq. in., and a temperature of 750° F.

The ship contains two electrical power stations, producing 8,800 kW. of electricity. This is sufficient to light a city containing 300,000 thirty-watt electric lamps. The ship contains 30,000 lamps and 4,000 miles of wiring. There are 650 electric motors of various kinds, ranging from ¼ h.p. to 360 h.p., and developing altogether 16,500 h.p. There are 700 electric clocks and 683 telephones.

These figures will give an idea of the tremendous work involved in the design and construction of such a ship. Her builders, Messrs. John Brown of Clydebank, made very extensive researches on models of the hull in their experimental tank, in order to discover the properties of the ship and forecast how she would behave. The conditions that occur in the Atlantic, the waves of immense length and height that are raised in Atlantic storms, the effects of gales, were reproduced in miniature in the tank. More than 7,000 experiments on many different models were made before the final form was settled. The models themselves were sailed up and down the tank more than 1,000 miles altogether.

As ships become bigger and bigger, their hulls become more elastic and jelly-like in properties. The forecasting of their strength becomes more and more complicated. During the designing of the ship, extensive researches were made in order to calculate its strength, and to determine the proper size of frames and thickness of plates and distribution of material and weight.

Apart from the ship, various preparations in the River Clyde became necessary. The river had to be widened, in order to permit the launching. Big lifts were erected to carry the workers from the ground to the decks 100 ft. above.

The ship has two bottoms, which form a 'ship within a ship'. The distance between the inner and outer bottoms is six feet, and the intervening space is divided into many watertight compartments.

Transversely, the ship is divided into 140 watertight compartments. Above these, there are steel bulkheads to prevent fire from spreading.

The stern frame, including shaft brackets and rudder, weighs 600 tons.

The hollow rudder contains a ladder inside, so that the inner walls can be inspected.

The preparation of the ship for launching was begun in August 1938, and the launching occurred on 26th September, one day before the crisis at Munich on 27th September 1938.

It had been intended that the *Queen Elizabeth* should make her maiden voyage in 1940, the centenary year of the Cunard Company. When war broke out in September 1939, she was still in the shipyard and uncompleted, and a sitting target for aerial attack. Presently it was decided to get her advanced with all speed, so that she could be removed from this danger as quickly as possible.

It was decided to send her to New York, across 3,000 miles of the Atlantic in winter, without the usual trials. Though the ship was theoretically fast enough to evade submarine attack, she had never been to sea. Her owners decided to risk the run to New York, in spite of the lack of trials. As the departure of such an immense ship could not be concealed, she was ostensibly prepared for a voyage to Southampton. She was fuelled with oil and loaded with stores, and a crew of 500 signed on for the coastwise run to Southampton. In the meantime, complete preparations were made for her arrival in Southampton, and the Southampton Pilot was brought to ship on the Clyde.

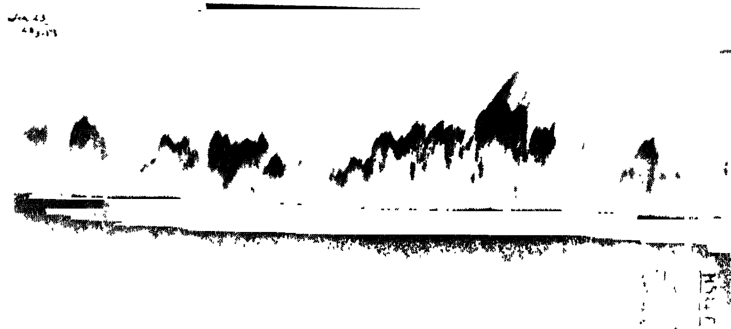
The ship left her fitting-out basin on 26th February 1940, escorted by six tugs. Her builders tested the steering gear and compasses, and handed the ship over to the owners on the following day. Her crew were then told of her destination and nearly all agreed to stay with the ship.

The *Queen Elizabeth* sailed early on 2nd March, and five days later arrived safely in New York. Her construction was completed there, and in November she sailed for Singapore, to be fitted out as a troop-carrier. In April 1941, the *Queen Elizabeth* sailed from Sydney with 5,600 troops, being accompanied by the *Queen Mary* in the same convoy. She carried Australian and New Zealand troops to the Middle East, she carried troops to India, and American troops to Australia when that continent was threatened by the Japanese. She took reinforcements to the 8th Army in Northern Africa, and then American troops to join in the invasion of Europe. By extensive reconstruction of the accommodation, her troop-carrying capacity was raised to 15,600. She carried a whole division across the ocean in one voyage, again and again and again. On her return journeys she carried varied complements of service personnel, diplomats, industrialists, scientists, engineers, and prisoners. In March 1945, she carried 3,300 American wounded, accompanied by 400 medical staff, from the Clyde to New York.

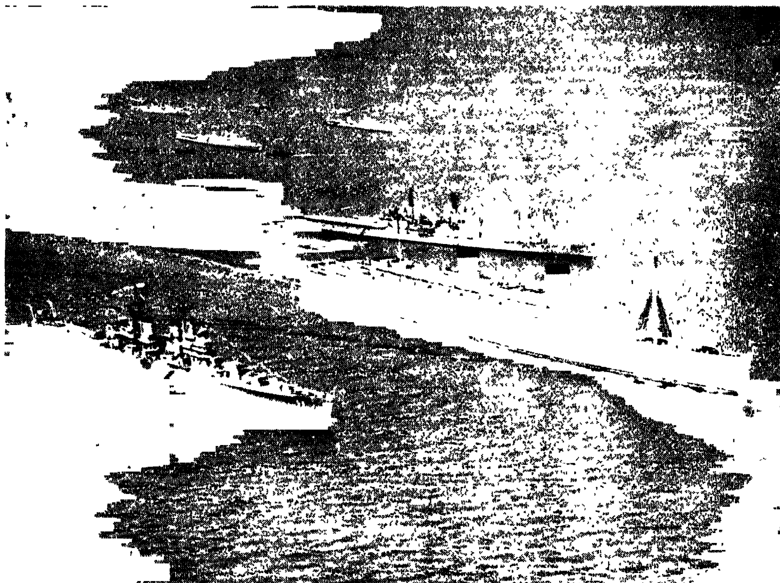
By the end of 1944, the *Queen Elizabeth* and *Queen Mary* had trans-



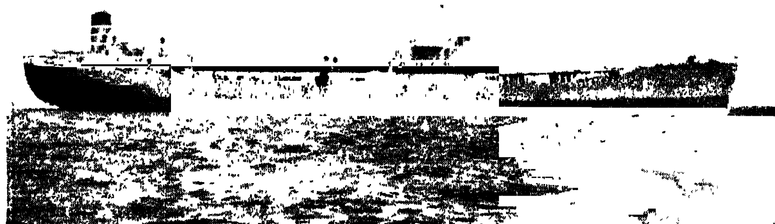
XLV*a*. Fixing the inner skin on the R.M.S. *Olympic*



XLV*b*. A trace on the recorder of a shoal of herring located by the Kelvin-Hughes echo-sounder



XLVI*a*. R.M.S. *Queen Elizabeth* sailing through the Fleet at Spithead at the Coronation Review



(*Petroleum Information Bureau*)

XLVI*b*. A British tanker of 12,250 tons deadweight

ported 944,000 troops, more than 80 per cent of them from America. By 31st May 1945, the total had risen to 1,243,538.

The reconditioning of the ship for civilian use began in March 1946. In June, the ship was sent to Southampton, where 1,000 workers of Messrs. John Brown, housed in a special camp at Chandlersford, together with hundreds of other skilled men, painters and decorative artists, completed the finishing and furnishing. Ten miles of carpets, and other furniture, which had been stored during the war, were laid down and fixed, and the ship prepared for her first voyage as a civilian passenger liner on 16th October 1946.

The main lines of the *Queen Elizabeth* and the *Queen Mary* are similar, but there are considerable secondary differences.

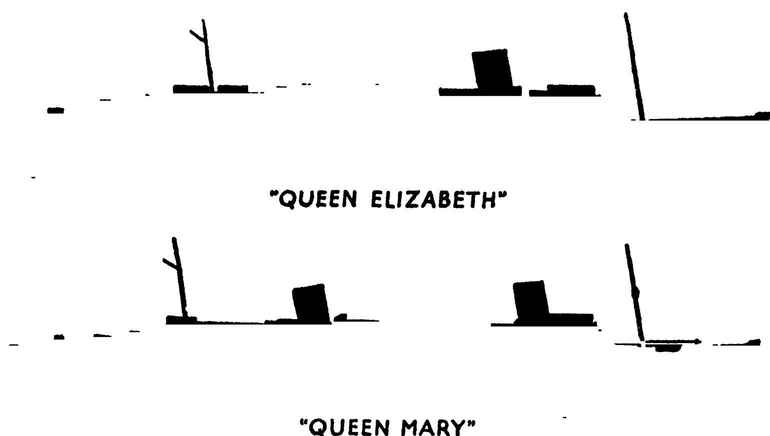


Figure 86. The profiles of the two 'Queens' compared

The most prominent is that the *Queen Elizabeth* has only two funnels. This has provided much more open deck space, a larger clear area for sports and promenades, and more accommodation for passengers. (The *Queen Elizabeth* takes 2,288 compared with the *Queen Mary's* 2,038.)

The *Queen Elizabeth* has three anchors compared with her sister-ship's two. The third is let down over the centre of the bow. In order to ensure that it falls clear of the hull, the rake of the bow is increased. Consequently, the *Queen Elizabeth* is 10 ft. longer than the other ship. The forward well-deck on the *Queen Mary* was replaced by a flush deck in the newer ship. These various changes account for the increase in gross tonnage from 81,337 to 83,673.

The bridge is 125 ft. wide and 90 ft. above the water. It contains a battery of telegraphic controls for the four turbines. There are gyro and

magnetic compasses, the controls for the 56 bulkheads, loud-speaking telephones which communicate with the chief parts of the ship, and the control for three powerful steam whistles.

In the chartroom is the master-clock which controls all the other 700 electric clocks in the ship.

There are two medium-wave radio direction-finders, and the LORAN (long range aid to navigation classified as radar), in addition to radar detector equipment. There are two portable transmitters, whose range can be doubled by means of a rocket kite aerial. Two of the twenty-six motor lifeboats carry radio telegraph and telephone equipments, with batteries which will keep them in operation for a considerable time. A low-power radio-telephone system is installed on the bridge for facilitating the control operations. There is a system of thirty-two powerful loudspeakers controlled by a single switch on the bridge, through which instructions can be given instantly in an emergency to the whole ship's company.

The steam for the ship's turbines is provided by 12 water-tube boilers. These are fitted with super-heaters and large air pre-heaters. They work at 425 lb. per sq. in. pressure and 750° F., compared with the 400 lb., 700° F. of the *Queen Mary's* 24 boilers (Plate XLVII*b*).

The four main engines, which consist of quadruple expansion single reduction geared turbines, are contained in two engine-rooms, the engines in the forward room driving the outer screws, and those in the after room the inner screws.

Each of the four propelling units can be operated independently, for manœuvring purposes. Each unit consists of four turbines working at successively lower pressures, together with a condenser. The high pressure, first and second intermediate pressure and low pressure turbines in the unit independently engage and drive the gear wheel on the forward end of one of the propeller shafts. Each turbine delivers its own drive through a single reduction helical gearing with teeth of involute design, so that the rate of revolution is reduced to that of the propeller shaft.

Turbines for propelling the ship astern are incorporated in the casings of the second intermediate pressure and low pressure parts of each of the four main engines.

The four 32-ton propellers are four-bladed, and made of manganese bronze.

The oil fuel is carried in side bunkers, and in double bottomed tanks under the turbo generator rooms. There are five points for pumping the fuel in through hoses. No manual labour is required, and the whole operation can be completed in eight hours, without interfering with the re-loading of the ship or the disembarkation of passengers.

The ship is steered through a massive tiller attached to the rudder

stock. The tiller is moved by four hydraulically operated pistons. These consist of single-acting rams in four cylinders, which are driven by oil under pressure. The oil is pumped into the cylinders by electrical pumps, which can be instantly controlled from the bridge. It is arranged that one, two, or three of the cylinders can be operated independently or in a desired combination (Plate XLVII*a*).

All of the deck machinery such as capstans, boat winders, steering gear, is electrically operated.

Electrical power is provided from two power plants built on opposite sides of a centre line watertight bulkhead, so that if one fails the other may keep working. Each of the two power stations contains two dynamos capable of producing 2,200 kW. Normally, one of these will be idle. Each station supplies power for the hotel services on the ship and for the auxiliaries for the propulsion machinery. The two power plants can function independently, or can be coupled together.

Additional safety is ensured by a small emergency electricity generating plant. This is installed at a distance from the main power stations, and consists of the two 750 kW. generator sets, each driven by Diesel engines equipped with quick starters.

The electrical communication equipment includes four radio transmitters, arranged so that the transmission and reception of messages, radio telephone calls, and safety of life precautions can be conducted simultaneously, and without interference.

First-class passengers can pick up the telephone beside their bed and speak to a friend or business colleague in any country with an international telephone exchange, or on another ship with radio-telephone equipment. Speeches and programmes can be broadcast from the ship, which can become for this purpose a station broadcasting to the world.

The internal climate of most of the public rooms of the ship is kept in equable conditions of temperature and humidity, through a variation of outside temperature from 100° F. to 0° F., by a huge air-conditioning system, operated by twelve independent air-conditioning plants. These are capable of delivering 10,000,000 cubic feet of conditioned air per hour. More than 100,000 sq. ft. of cork are used in the insulation of the plant and the supply ducts.

The ship contains a fire station which is always manned. It is the centre of a very elaborate fire control system. Indicators from all parts of the ship register fire-dangers at once. Pipes from the holds, baggage rooms, and other spaces, provide means of detecting smoke arising in any of those places. If smoke should be detected, the place where it is being produced can be flooded at once with non-inflammable carbon dioxide gas. All inhabited spaces are penetrated by a sprinkler system, which automatically comes into operation above a certain

temperature. The stores for a round Atlantic voyage of the *Queen Elizabeth* include:

Beef	14,000 lb.
Lamb	10,000 lb.
Ham	7,000 lb.
Jam	3,600 lb.
Flour	300 bags
Sugar	7,000 lb.
Butter	7,000 lb.
Eggs	72,000
Fresh Milk	1,500 gallons
Dried Fruits	1,400 lb.
Potatoes	20 tons

The furniture includes:

Linen	100,000 pieces
Blankets and Eiderdowns	8,000
Carpets, Bedspreads and Loose Covers	13,000
Bedroom Carpets	2,500
Public Room Carpets	60
China and Earthenware	54,000
Knives	10,000
Forks	10,000
Spoons	6,750
Glassware	26,000 pieces

The thirty-five public rooms contain an immense variety of decoration. Among the woods used are lime tree, London plane tree burr, English elm burr, sycamore curl, English poplar, English olive ash burr, myrtle burr, sycamore died to the colour of a lobster shell, Canadian maple cluster. The First Class Smoking Room is panelled from the various parts of a giant chestnut tree that grew in the Isle of Wight. The Cinema Theatre is decorated by small lighthouse lenses. The walls of the Verandah Grill are covered with ivory coloured sycamore veneer. The walls of the Swimming Pool are covered with a latex composition filled with Mother of Pearl chippings.

Thirty-seven different types of design were used in decorating the staterooms. Each contains a three-speed electric fan and an electric radiator which can be regulated.

The cabin accommodation includes a children's playroom with a miniature replica of a ship's bridge, with small-scale telegraphs, speaking tube, steering wheel and binnacle. The steering wheel is geared to an endless panorama, which produces for the children on the bridge the illusion of sailing through arctic and tropic seas.

The Tourist Restaurant is decorated with Canadian birch and Australian walnut. The Smoke Room has straight-grained elm.

Such are some of the features of the accommodation for those being

carried across the Atlantic in less than four days at an average speed of perhaps 31 knots, or nearly 36 miles per hour. When two such ships pass each other in opposite directions, as may happen in mid-Atlantic, their relative speed is 72 miles per hour. They race into each other's sight, and vanish again, like an express train which disappears in a few minutes into the distance.

SHIPS FOR SPECIAL PURPOSES

In contrasting present-day types of ships with those which were to be seen in the 'eighties nothing is more remarkable than the development of special forms to meet the changing needs of industry and commerce. For example, although in 1886 petroleum ranked fourth in the list of American exports, nearly all of it was shipped in iron casks or wooden cases lined with tinplate. Mr. J. Montgomerie, M.I.N.A., writing in the special marine number of *Cassier's Magazine* in 1911, stated that the vessels engaged in the trade were mostly wooden sailing ships belonging to foreign owners; and he attributes the growth of the modern oil-carrying vessel to the enterprise of British shipbuilders. By 1893 there were eighty vessels of an average tonnage of 2,500 engaged in the trade, and in 1952 there were 2,366, each of 2,000 or more deadweight tons. Several tankers of 31,000 or more deadweight tons are at present in actual service. The largest tanker launched—though not in commission by 1952—is of 38,000 deadweight tons. Altogether, the world's tanker tonnage now totals at least 31,054,442 deadweight tons.

The size of tankers has increased sharply since the Second World War to an average deadweight tonnage of 16,000–18,000.

The modern oil-carrying ship is called an oil-tanker, because the oil is contained in tanks which occupy the bulk of the ship. She is loaded by pumping the oil into her, and unloaded by pumping it out, but whatever simplicity attends this method, the design involves special problems which require skill and judgment to overcome them. It is probable that the reader may ask why the vessel is divided up into tanks—why not utilize the whole of the hold in one or at most two or three compartments? The main reason is that oil is not a fixed and immovable cargo. Any motion of the vessel would set it oscillating from side to side, or surging fore and aft in the hold. Moreover, any motion given to the oil might coincide with its natural period of vibration, and the force exerted by several thousand tons of oil would burst the decks or capsize the ship (Plate XLVI*b*).

In a modern oil-tanker the tanks occupy nearly the whole length of the ship. They are about 28 ft. long, and each one is divided by a longitudinal bulkhead. Each half of a tank is provided with a sort of neck in the upper portion to allow for expansion. Vacant spaces are left between

the fore and aft end tanks and the cargo hold and engine-room for safety. They are known as coffer-dams and serve to isolate the oil from any part of the ship in which it might become ignited. The engine-room is in most vessels placed at the after end of the ship, partly because the cost of constructing a tunnel for the shaft through after tanks is thus avoided, and partly because this arrangement increases the amount of space for oil. The lighter varieties of oil give off a highly inflammable vapour, and exceptional precautions have to be taken to prevent the cargo catching fire.

Another striking application is the train-ferry. The *Drottning Victoria* built by Messrs. Swan, Hunter & Wigham Richardson, for service in the Baltic, was about 370 ft. long, 53 ft. beam, and over 4,000 tons displacement, with a speed of 16½ knots. The main deck had two lines of rail each nearly 300 ft. long, and capable of receiving four coaches. The vessel had large tanks into or out of which water could be pumped to alter her depth of immersion or 'trim' so that the train could be run directly on to her rails over a bridge or gangway. The wheel frames of the coach were chained tightly to the deck to prevent movement on the journey, and hydraulic jacks between the rails were used to lift the bodies of the coaches off the springs. The journey was made at night, and there was no need for passengers to leave their sleeping berth in the train.

The development of traffic on the great Canadian lakes, which has been enormously increased since they were connected by canals, such as the famous Sault Ste. Marie between Lake Superior and Lake Huron, has demanded a special type of steamer. Here the water is comparatively still, and the material to be carried is ore and corn in bulk. Ships can therefore be employed which have an enormous carrying capacity, but of a form which would render them extremely unseaworthy in rough water. Their speed through the canals is limited to 4 m.p.h., but in view of the short distance between the locks they must be able to start and stop very quickly. A screw of special form is used, having wide blades. The horse-power required is only 150. On the lakes a speed of about 10 m.p.h. is usual, and 750 h.p. is required.

The navigation of rivers presents special problems to the shipbuilder. The small size of Great Britain, the shortness of her rivers, the possibility of having ports at or near their mouths, and the excellence of her railway system, render it difficult to realize the importance of natural waterways in large continents. Only a vague conception exists of the enormous traffic on rivers like the Danube and the Mississippi. If rivers like these are important in highly civilized countries possessing a not inconsiderable railway system, how much more vital must they be for example in Africa where the forest resents even the narrow clearing demanded by a railway line. Since the British railway companies bought

up the canals and permitted them to fall into disuse the Englishman has grown up with no tradition of the value of the narrow waterway as an alternative to the macadamized road or the steel track.

Generally speaking, the rivers which lend themselves to navigation are slow-flowing, sluggish streams, which amble along shallow depressions, and do not carve out for themselves the deep channels that the ordinary ship demands. Even in the case of ports which are situated at the mouths of rivers dredgers have to be kept constantly at work to remove the silt which the river deposits on its way to the sea; and Glasgow is a standing example of a port that owes its growth and existence to extensive and persistent dredging. The mouth of the Clyde has been literally scooped out of the earth during the past hundred years.

The characteristic of most river steamers, then, is shallow draft, and many of them must not draw more than 18 in. of water. They are more like flat-bottomed houseboats, with great breadth of beam, and all their accommodation for cargo and passengers above the water-line. A common form of propulsion is a single paddle wheel mounted over the stern, but A. F. Yarrow constructed river boats with a screw working in a tunnel with a hinged flap at the after end. A screw having a diameter more than twice as great as the draught of the boat can be used, because, once it has started rotating, it throws up the water until the tunnel is completely full. For high efficiency the upper surface of the tunnel should be nearly horizontal, and yet, especially at starting, the opening should be wholly beneath the surface. If the latter condition be fulfilled when the boat is loaded it will not be fulfilled when she is light. Yarrow therefore attached the upper surface of the tunnel, from the screw aft, to a hinge, so that it could be adjusted with the outer end a few inches below the surface whatever be the load carried. Increased speed is obtained without increase of power, and the engines work with maximum efficiency under all conditions of load.

MARINE PROPULSION

The means of propelling ships is at the present time undergoing a remarkable upheaval, and the result of the extensive experiments which are being carried out will in all probability be half a dozen different forms, each specially suited to some particular service. Considering first steam-power it may be remarkable that the triple or quadruple expansion engine has held sway for more than thirty years. It is efficient, gives a large power at a reasonably low speed, and is thoroughly understood by the present generation of sea-going engineers. When the turbine was first introduced it used a large quantity of steam—about 16 lb.—per horse-power, but this has been reduced to 10 lb. or less, and this is quite as small as can be shown by any reciprocating engine working

under similar conditions. Moreover, it occupies a much smaller space and leaves more room for cargo. As compared with the reciprocating engine it has, however, at least two disadvantages—non-reversibility and high speed. Large engines of any type whatever run at slower speeds than small ones, yet the turbines of the *Mauretania* made 700 r.p.m. The non-reversibility has been overcome by fitting 'astern' turbines on each propeller-shaft, which are usually capable of giving half the power.

Within recent years three other methods have been tried, and each seems likely to have an extended use in particular circumstances. One is to connect the turbine-shaft to the propeller-shaft by means of gearing, and has been rendered possible by the improvements of Sir Charles Parsons in the cutting of toothed wheels, to which reference has been made in a previous chapter.

Another method is to use electricity. The steam-turbine is at its best when driving a dynamo, and the current is used to drive electromotors mounted on the propeller-shaft. Reversal is then effected by means of a reversing switch. Electrical drive was adopted extensively in the American Navy, and possesses great flexibility.

The supremacy of the steam-engine has been challenged during the last twenty years by the Diesel heavy oil-engine. In Chapter IV some account is given of the saving in space, and Chapter II contains a statement of the special value of oil-fuel. To the points there enumerated may be added the reduction in the amount of auxiliary machinery. Those who have not actually seen the engine-room of a steamship can have no conception of the complicated mass of machinery it contains. Apart from the engines which turn the screws, there are condensers, air-pumps, feed-water purifiers, and a host of indispensable appliances which use power, take up space, and materially increase the possibilities of breakdown. By comparison the oil-engine is far simpler, but at present there appears to be some difficulty in building engines of large power. About 6,000 h.p. was the maximum for any one 'set', or from 1,000 to 1,500 h.p. per cylinder. For cargo boats the Diesel engine had achieved a rapid and extraordinary popularity, and more than half the world's tonnage launched in recent years is dependent upon oil fuel. But there will still be a question of fuel sufficiency, and many believe that coal will always, so far as can be seen at present, be a major fuel for marine propulsion.

It must be borne in mind that all this work is of very recent growth. The first large ships to be equipped with steam-turbines were the Allan liners *Victorian* and *Virginian*, and the Cunarder *Campania*—all three in 1905. Combined reciprocating engines and low-pressure steam-turbines were first used in the *Otaki*, belonging to the New Zealand Steamship Company and showed a fuel economy 12 per cent over a sister ship fitted with reciprocating engines only.

The geared turbine was introduced in 1910, and a cargo steamer of the Caira Line built by Messrs. Doxford of Sunderland showed 15 per cent economy over reciprocating engines.

During the last thirty years the geared turbine has outstripped its competitors for fast passenger ships, and its success has been due very largely to the invention of the Michell Thrust Block. When the propeller is rotating it is forcing the water backward and the 'reaction' which causes the ship to move forward is communicated to the ship through the propeller shaft. In order to take this thrust it was customary for the propeller shaft to be furnished with a number of collars or flanges, which pressed upon a number of 'horse-shoes' fixed to the frame of the ship. These plates were faced with anti-friction metal, and kept cool by circulation of water when high-powers were involved. This multicollar thrust block was elaborate and costly, it occupied a great deal of space, and it required very careful and accurate adjustment to equalize the pressure on the horse-shoes. But once adjusted it worked well with reciprocating engines.

When turbines were introduced they were mounted on the propeller-shaft, and as the steam acted on the turbine blades in such a way as to oppose the thrust on the main shaft, a thrust block on the main shaft was not necessary. But in a geared turbine the thrust block had to be reintroduced, because the steam no longer acted on the propeller shaft. Then the multicollar thrust block broke down for reasons which will be apparent after we have devoted a little attention to the mechanics of lubrication.

The theory of lubrication was worked out many years ago, experimentally by Beauchamp Tower and mathematically by Osborne

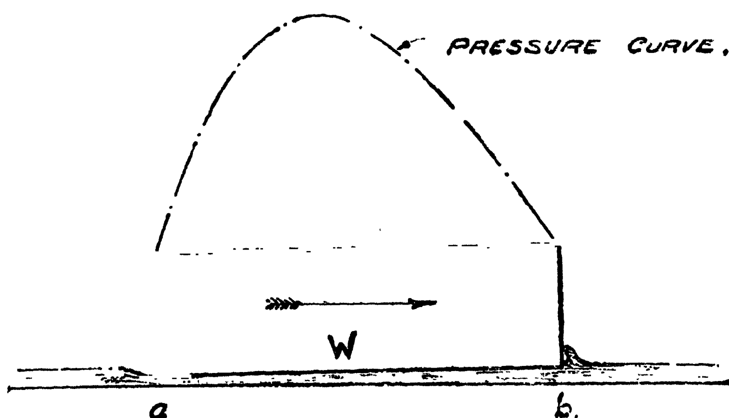


Figure 87. Formation of pressure oil film in a bearing

Reynolds. If a 'block W is loaded and moves over a lubricated surface in the direction of the arrow, the edge *b* must lift to allow the lubricant adhering to the stationary surface to enter the film space. *The block mounts over the oil!*' Consequently surfaces are most effectively lubricated when the film of oil is wedge-shaped, tapering in thickness

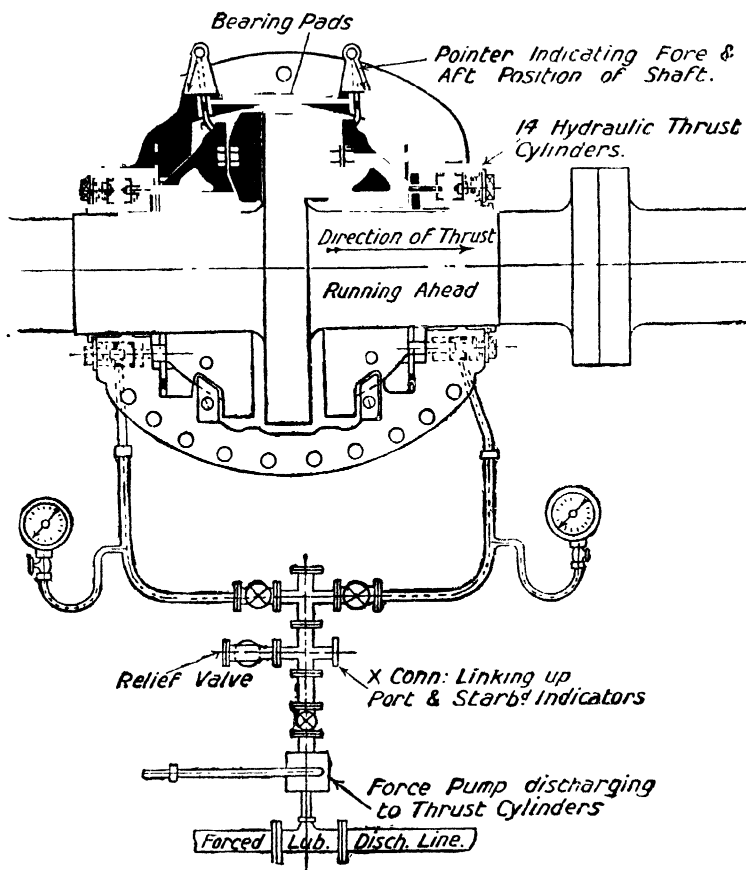


Figure 88. Michell thrust block, fitted with apparatus for indicating the thrust

towards the rear. In order to fill this wedge-shaped space, the oil exerts pressure, and will begin to flow into such a space as soon as the rubbing speed exceeds 7 ft. or 8 ft. per minute. If the surfaces are both stationary and oil is forced between them, the lines of flow between the surfaces are not parallel. The oil enters at the front edge and leaves at the sides as well as the back as shown in Fig 87. Unless the front is lifted the

lubricant cannot enter with sufficient rapidity, cavitation or thinning out occurs, and friction with consequent overheating result.

With a reciprocating engine it was not difficult to keep a multicollar thrust block lubricated, because the unevenness of motion caused a slight rocking which destroyed the parallelism of the surfaces in contact. But the motions of the turbine and its geared shaft are so uniform that no wedge is formed, any oil present was squeezed out, and the bearing 'ran hot'.

Some years before this problem arose A. G. M. Michell, of Melbourne, had invented a thrust block which had small blocks, capable of rocking about a point or a line, on the face of the horse-shoe. As soon as the shaft begins to rotate the blocks rock and form wedges into which the oil flows, and the friction under similar conditions is only one-twentieth of that which occurs between fixed flat surfaces. Fig. 88 is a half-section of a marine type thrust block fitted with an arrangement for indicating the magnitude of the thrust.

A Michell Thrust Block 7 ft. long replaces a multicollar thrust block 25 ft. long and three times its weight. A single collar only is necessary, and owing to the rocking blocks the thrust may safely be 200 lb. or 300 lb. per sq. in. compared with 20 lb. or 30 lb. per sq. in. for the older type, and there are blocks in use transmitting no less than 25,000 h.p. through a single shaft.

THE GYRO COMPASS

For a thousand years the mariner has navigated the ocean by the magnetic compass. A small needle or needles attached to the under surface of a graduated card have enabled him to plot his course from hour to hour and from day to day. When the sun and stars were obscured by fog or cloud, the small instrument in the brass case has enabled him to steer his ship with the certainty and confidence that come of long experience. He has discovered new lands, brought North and South, East and West into communication and made the whole world kin. Definite ocean highways have been established, and sea voyages are carried out with a punctuality that depends upon the navigator and his instruments no less than upon the engineer and the powerful forces he controls.

The use of iron and steel in place of wood for ships conferred size and safety, but led to special difficulties of navigation. Any mass of iron or steel influences and is influenced by a magnetic needle; and the enormous masses of magnetic metal in modern ships are liable to exercise an effect upon the direction of the compass needle which entirely overshadows that of the earth. Special adjustments are necessary, and the readings have to be checked from time to time.

But with the dawn of the new century experiments were undertaken which have resulted in an instrument that will point a north and south direction quite independently of the nature of the material of which the ship is made, and the gyroscope, which has for years been a popular scientific toy and had found a single permanent application in the torpedo, seems destined to guide the world's shipping with a certainty that the frail compass needle under the new conditions could never achieve.

A gyrostat is simply a heavy wheel, the axle of which is mounted in a ring (Plate XLVIII*b*). When the wheel is set rotating at high speed, either by means of a piece of string or by pressing the pulley wheel of a small electromotor against the axle, it resists strongly any attempt to twist the wheel so as to alter its plane of rotation. Few things are more striking than the way in which any attempt to move the frame in any direction except one in which the axis remains parallel with itself is met by a vicious 'kick' which, if the wheel is a heavy one rotating at high speed, almost throws the apparatus out of one's hand.

This kicking propensity of the instrument is really the source of its usefulness, and it will be interesting to observe the exact effect of the twisting force upon it. If the simple form already illustrated is suspended by a string, as in Plate XLVIII*b*, and pressure is applied to one end of the axis by a pencil for example, the wheel tends to turn in the direction of the arrow marked on the horizontal ring. The wheel and its axle turn in a direction at right angles to the force which is applied, and the rotation of the axis is known as *precession.* If the pencil is applied to the other end of the axis, the rotation is in the opposite direction.

These results are more easily observed in Wheatstone's Compound Gyrostat, in which the wheel is mounted in two rings capable of rotating about axes at right angles to one another. Such an instrument is illustrated in Plate XLVIII*a*. The force is applied by hanging a small weight to one end of the axis, and so long as it remains the precession is continuous, while immediately it is removed the precession stops.

If the axis is caused to rotate, then a force is produced at its ends, and a 'kick' is produced in a direction at right angles to that about which the turning takes place. This reverse effect is illustrated in Plate XLIX*a*. Gyroscopes or gyrostats mounted in this way—so that they are capable of rotation about three axes at right angles—are said to have three degrees of freedom. If one of the possible rotations is prevented, then the rotating wheel will have two degrees of freedom, and it is a gyrostat with two degrees of freedom that is suitable for use in navigation.

In order to understand how this result has been achieved it is necessary to recall the pendulum experiments of the famous French physicist Foucault, conducted about the middle of last century. He showed that

if a pendulum were set swinging and were subject to no disturbing influences, it would maintain its original plane of vibration throughout; and though the earth might be turning beneath it, the pendulum would still swing to and fro in the same absolute direction as that in which it was started.

This, in fact, provides one of the most beautiful methods of proving that the earth itself rotates. Foucault set up a long pendulum carrying a small pointer beneath the weight or bob. This pointer traced a line in sand as the bob passed through the lower part of its path, and as the earth rotated on its axis the line in the sand showed more and more deviation from the original trace.

The rotation of a heavy wheel at high speed produces a more powerful tendency to maintain the original direction of motion than does the to-and-fro motion of the pendulum bob; and Foucault concluded that any gyrostat with three degrees of freedom would indicate the rotation of the earth in the same way. In other words, such a gyrostat would maintain its original direction independently of the movement of the body to which it was attached. Moreover, he stated that a gyrostat with only two degrees of freedom would, at any place on the earth's surface except the two poles, tend to set itself with its axis of rotation parallel to the axis of the earth. For consider the cases presented by Plate XLIX*b*, in which a gyrostat at A, with its axis horizontal, has three degrees of freedom. When, owing to the earth's rotation the gyrostat has moved to A_1, having maintained its original direction the axis is not now horizontal, but the black end dips downwards. If the gyrostat is suspended by a thread as a pendulum, or supported by means of a float, in such a way as to keep the axis in the horizontal, this constraint gives rise to precession in the direction indicated by the curved arrow D. The ultimate result is to turn the gyrostat so that the axis points true north and south.

At the time when Foucault arrived at his conclusions mechanical science and accuracy of workmanship were insufficient to enable a practical demonstration to be made. It was not until the use of steel for ships, and particularly ships of war and submarines, had enormously increased the difficulties of compass adjustment that the need became great, and even then the theoretical and practical obstacles effectively prevented a solution.

A GYRO COMPASS FOR SMALL SHIPS

In small ships there is little space for equipment, and the motion of the vessel in rough seas is considerable. Great efforts have been made to evolve a compact gyro compass which would meet these conditions. It should be self-contained, stand up to rough conditions, and require

the minimum of adjustment. The Sperry Gyroscope Company have produced the *Minor* gyro compass to meet these requirements. The complete instrument is housed in a binnacle 57 in. high, and 23 in. in diameter, the whole unit weighing approximately 300 lb. (Plate L*a*).

It is normally located in the wheelhouse. It can if necessary be used for the operation of compasses in other parts of the ship, which repeat its readings, and thus inform the navigating crew of the readings without the necessity of their going to the wheelhouse. It can also be used as a master-compass for controlling a gyro pilot, and other instruments.

The binnacle is divided into two parts. The upper part contains the meridian-seeking element of the compass, supported in its gimbal rings. The lower part contains the control panel, the amplifier, and the motor alternator.

The cover of the upper compartment is held in place by four catches. It contains windows through which two dials can be viewed. One dial has a standard card divided into 360°, and the other shows readings on graduations equivalent in size to those on a card 30 in. in diameter. This arrangement removes the need for optical magnification.

The lower part of the binnacle has two pairs of doors. When the top cover and the doors are removed, access is obtained to the motor alternator, the control and amplifier panel, and the terminal board.

The four supports consist of tubes which form part of the ventilation system. Air is drawn through vents at the bottom of the tubes and is discharged into the upper cover.

The motor alternator, which provides the current for driving the rotor, is of the inductor type, so that no slip rings are needed for leading in the current from the ship's electrical supply system. The alternator is wound to produce three-phase alternating current at 110 volts, with a frequency of 250 cycles per second. It runs at 1,880 r.p.m., and is controlled to that speed by a governor fitted on the motor alternator shaft. The governor keeps the speed constant, over a range of variation in the voltage of the ships current of plus and minus 15 per cent.

The three-phase alternating current produced by the motor alternator is used to drive the rotor of the compass at 15,000 r.p.m. The rotor runs in a case from which the air has been exhausted, in order to reduce friction. The vacuum should remain indefinitely, but if a leak occurs its presence is shown by the blowing-out of a bellows. The presence of air does not seriously interfere with the performance of the compass if it is not allowed to remain there very long. It should be removed as soon as possible by a gyroscope servicing engineer.

The electrical parts are controlled from a control panel in the lower binnacle. This contains switches and fuses, voltmeter and ammeter indicating the voltage and current on the gyro, amplifier valves, etc. When the gyro rotor is running at 15,000 r.p.m. the gyro voltage should

be 100–120 volts, and the current 0·25–0·35 amperes. If the voltmeter reading drops to 95 and the ammeter reading rises to 0·5 amp. a loss of vacuum in the rotor case is indicated.

The true heading for the ship is calculated from the bearings given by the compass with the help of a mechanical calculator.

On the correction calculator there are two knobs, one dealing with the latitude, and the other the speed. The navigator fixes these on the respective scales by turning the knobs. He then performs a series of operations with other knobs, until a red line is brought to coincide with the true course required. In order to make this true course, it is necessary to steer the compass course as indicated by a white line. The difference between the readings of the red and white lines represents the correction necessary to make good the true course.

While the gyroscopic compass was used in special vessels from the first decade of the twentieth century, it was not generally adopted in the Royal Navy until its value had been demonstrated in the First World War. This followed on the outcome of the battle of the Falkland Islands. Two British battlecruisers were urgently needed to destroy von Spee's squadron and thereby secure control over the South Atlantic and South Pacific. But their magnetic compasses needed adjustment, which threatened a vital day's delay. They were sent off with experimental Sperry gyro compasses which were immediately available, and arrived at the Falkland Islands in record time, coaled, and steamed out again, and were able to take von Spee's squadron by surprise.

The first merchant vessel to adopt the gyro compass was the liner *Aquitania*, in 1919.

Besides steering ships, gyroscopes are used for stabilizing them. The steamship is much more liable to roll than the sailing ship, as the sails on the high masts act as stabilizers. From an early date, efforts were made to find an alternative form of stabilizer for the steamer, and efforts were made to utilize the gyroscope. The largest vessel equipped with a Sperry stabilizer was the Italian luxury liner *Conte de Savoia.* It consisted of three rotors each 13 ft. in diameter, and each weighing 110 tons. These rotors were made from steel forgings each weighing 125 tons.

Another form of stabilizer consists of retractable oscillating fins which can be projected from the side of a vessel, and damp down the rolling. These are operated under the control of a much smaller gyroscope.

The gyroscope is utilized in connection with many other devices. It can be used, through the medium of the gyro compass, as an automatic pilot. This is achieved by placing the gyro compass in control of the engine which operates the steering-gear, through a system of electrical connections.

The gyro-pilot can be adjusted to let the vessel have a small amount

of 'weather yaw', and the amount of rudder applied for a given amount of departure from the set course can also be varied. It can steer a loaded ship as well as a light one, and is effective in heavy weather, as well as in a smooth sea.

Automatic steering can be more accurate than human, and hence more economical. Three helmsmen out of four tend to favour one or the other of the two sides of a set course. The gyro-pilot does not, and keeps to within a quarter of a degree of the set course. It detects the 'off course' movement earlier, and makes the necessary small correction before the 'yaw' has become considerable.

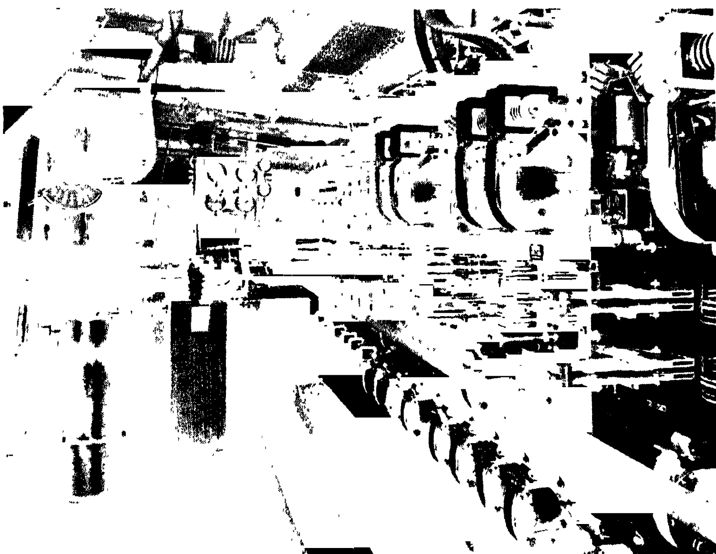
Bad steering may cause a waste of as much as 2½ per cent of the fuel burnt. During a comparison of human and automatic steering under average conditions of wind and weather, it was found that 133 turnings of the rudder were necessary in half an hour by hand steering, and only 49 in the following half-hour, by automatic steering. The vessel made 10·7 knots with hand steering, and 10·85 with automatic steering, i.e. a gain of 1·4 per cent in speed. If the vessel were at sea for 210 days in the year, she would cover 54,683 nautical miles by automatic steering, compared with 53,928 with hand steering. This would represent a saving of at least £76 per annum on fuel.

There was a marked improvement in all the ship's auxiliary machinery, owing to the elimination of back pressure in the exhaust system.

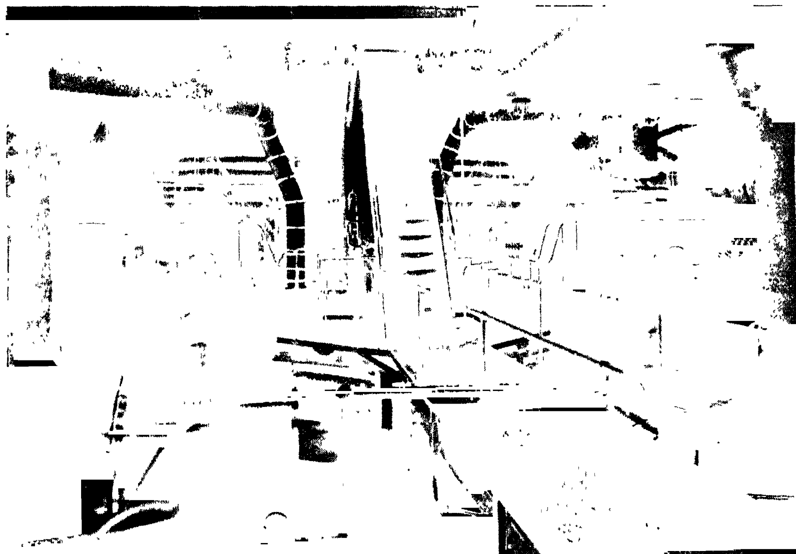
The use of manual steering in open waters is obsolete. If the quartermaster is released from the monotonous task of steering, he can give useful assistance to the officer on the bridge. It relieves the strain on the human being, and releases his energies for other purposes.

Lawrence Sperry won a prize of 50,000 francs in May 1914 for a gyroscopic stabilizer for aircraft. It consisted of four gyros mounted in a frame stabilized in the vertical. The frame actuated clutches, enabling a servo motor to control the aircraft by operating the control surfaces. The servo motor was driven by a fan caused to rotate by the slipstream. The gyroscopic stabilizer offered the prospect of safer flying under bad atmospheric conditions. The pilot was relieved of the fatigue of maintaining the equilibrium of his machine, and his hands were left free to draw maps, etc.

This early aircraft stabilizer was in advance of its time. Nearly twenty years passed before a satisfactory aircraft automatic pilot was produced. In the years immediately following 1914, the stability of aircraft was rapidly improved, owing to a better knowledge of aerodynamics, while the machines remained relatively small. The need for automatic pilots seemed to decrease. With the introduction of big passenger aircraft, making heavy demands on the pilot, and nevertheless requiring the highest possible safety for the passengers, the need for an automatic control which would lessen the strain on the pilot and thus increase



XLVII*a*. Steering gear and switchboard of R.M.S. *Queen Elizabeth*



XLVII*b*. General view of the engine room of the R.M.S. *Queen Mary*

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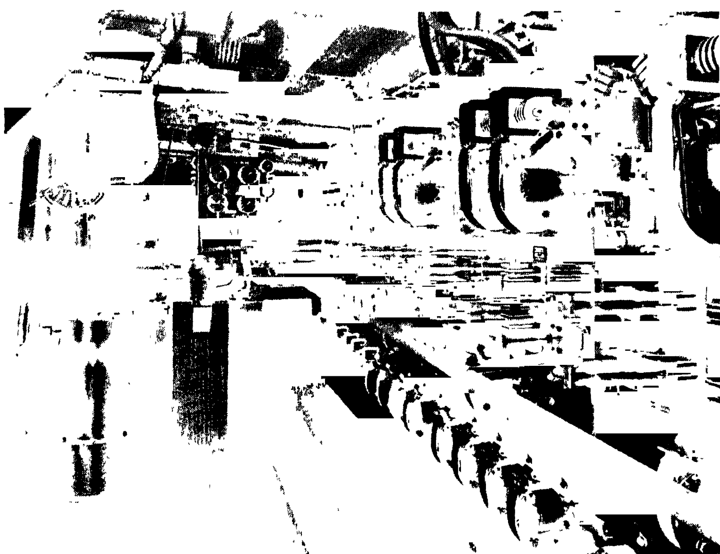
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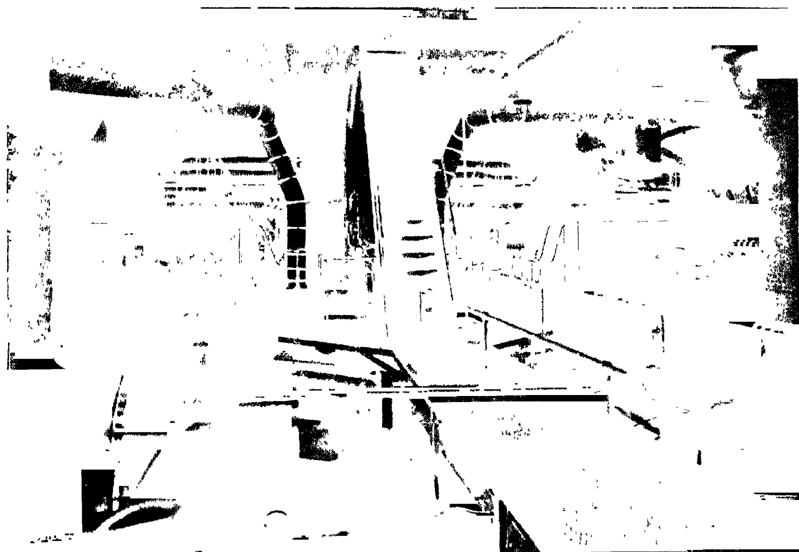
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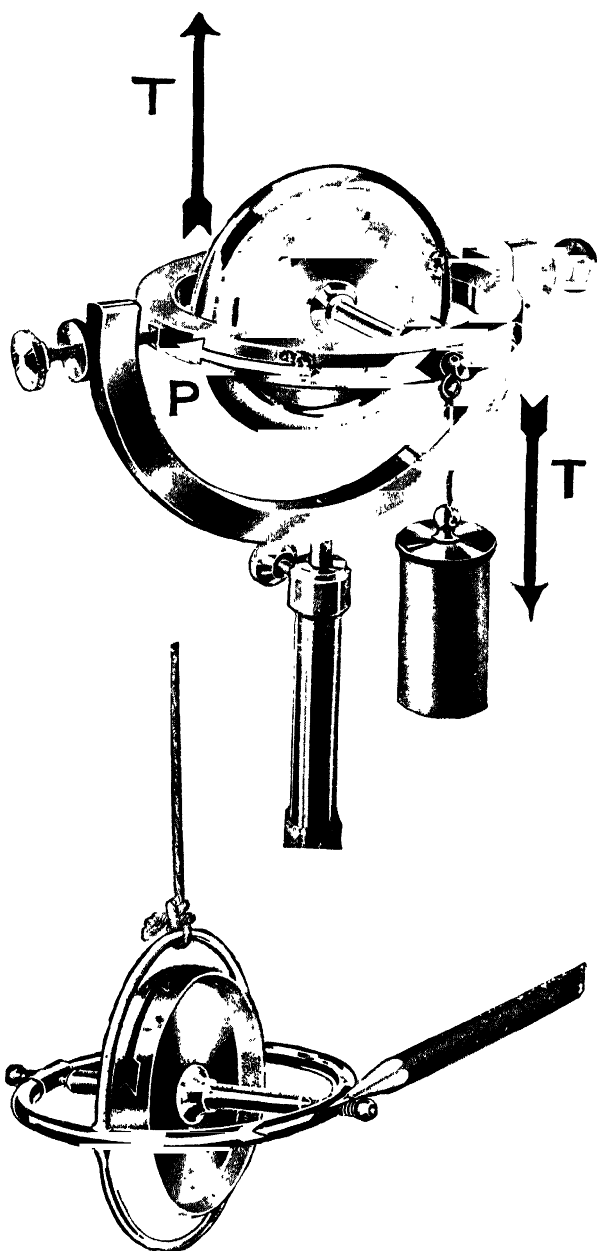
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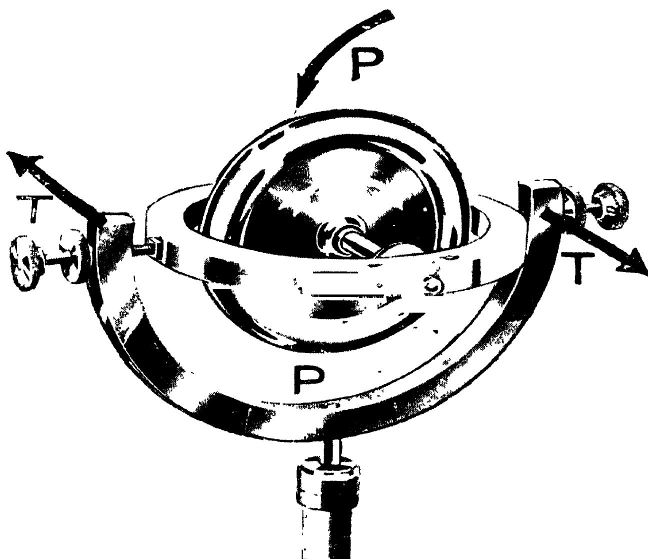
XLVII*a*. Steering gear and switchboard of R.M.S. *Queen Elizabeth*



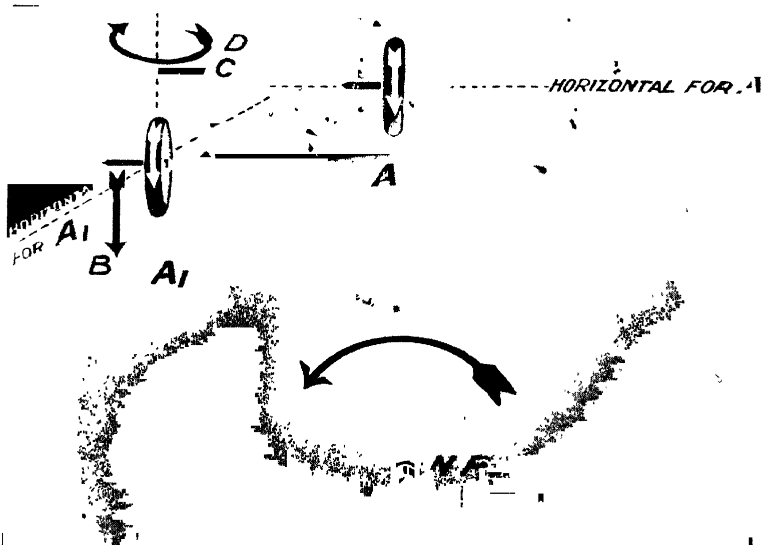
XLVII*b*. General view of the engine room of the R.M.S. *Queen Mary*



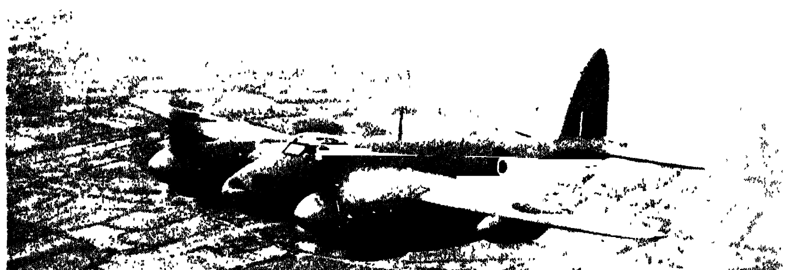
XLVIII*a*. Wheatstone's Compound Gyrostat, weighted to cause precession



XLIXa. The same as Plate XLVIIIa but couple applied to horizontal axis



1*a*. General arrangement of the Sperry Minor gyro-compass from forward



1*b*. De Havilland 'Mosquito' fighter bomber

safety, again began to grow. In the meantime, too, several other inventions had been developed, which made the perfection of the automatic pilot easier.

The Artificial Horizon, now known as the Gyro Horizon, provides the pilot with direct indication of his attitude in the lateral and longitudinal planes, and can be used as a substitute for the natural horizon for taking instrument observations. The human pilot sees his own attitude relative to the natural horizon represented by a miniature aircraft in relation to an artificial horizon set by a gyroscope. The Directional Gyro gives direction in azimuth, or elevation.

With the two instruments, flying and navigation by instruments alone becomes possible. In about 1930, a human pilot successfully circled and landed in an aerodrome with the aid of these two instruments, and without looking out of his cockpit. The remarkable flights of Post and Gatty, the Lindberghs, and Scott and Campbell Black were made with the assistance of these instruments.

THE AUTOMATIC AIRCRAFT PILOT

An automatic pilot for civil use was introduced in 1932. Post flew round the world, with one of these instruments as sole companion, in less than eight days. After switching in the gyro-pilot, Post could study his maps, operate the radio, and look out for landmarks. He dozed in short spells, with a waking device. On his last lap of 2,000 miles, from Edmonton to New York, he was able to take over one hundred of these naps, and thus succeed in keeping going.

In these early gyro-pilots, the directional and horizon gyros were air-driven. These detected deviations in azimuth, and pitch and roll. The corrective movements were applied to the aircraft control surfaces, elevators, rudder, etc. by means of pneumatic or hydraulic piston-type servo-mechanisms.

The Second World War stimulated the demand for still more stable aircraft, especially to improve accuracy in bomb-aiming. This led to the electrically-operated gyro-pilot, under instantaneous control through electronic equipment. This is the kind of automatic pilot fitted in the 'Comet' airliner, the 'Bristol 171' helicopter, and many other modern aircraft. It relieves the human pilot of all the fatigue of handling his aircraft for long periods, and leaves him fresh and free to devote most of his effort to the vital functions of take-off and touch-down.

The electronic gyro-pilot incorporates automatic approach control. This brings the aircraft along the airfield glide path, to within a few feet of the runway, when the human pilot takes over. This is particularly valuable when visibility is poor.

The electrically operated Gyro Horizon, being independent of

air-pressure, operates reliably at any altitude. Its rotor revolves at 22,000 r.p.m., compared with the 12,000 of the early air-driven type, and consequently gives a higher and more accurate performance.

The Gyro Horizon gives the position of the aircraft with reference to bank and pitch, or climb and dive. The heading (the azimuth or angle between a point on the horizon and the north and south line) can be determined accurately for a moment by the Directional Gyro, but this is liable to wander after a few minutes. It remains steady when the aircraft turns. The magnetic compass, on the contrary, is badly upset by turns, but gives accurate readings when the aircraft is in straight steady flight. The Directional Gyro and the magnetic compass have therefore been combined in the Gyro-magnetic compass. In the most modern forms as in the Gyrosyn compass, the alignment with the earth's magnetic field depends not on a moving magnet, but on a flux-valve. This contains no moving parts, but registers its azimuth orientation with regard to the earth's magnetic field. It depends primarily on the change of current in a coil due to its rotation relative to the earth's magnetic field.

The detector-unit weighs only 1½ lb. and can be fixed at any convenient place in the aircraft, e.g. at the wing-tip, remote from local magnetic disturbances in the aircraft.

The Gyro Horizon for helicopters presents the pilot with a continuous picture of the fuselage attitude, and together with a rate-of-climb indicator will show the flight-path which the aircraft is following.

The instrument is specially adapted for freedom from 'topple' about the axes of roll and pitch, and gives the datum positions for both cruising and hovering flight.

Another recent aid to the human pilot is the Zero Reader Flight Director. This is essentially a calculating machine which takes the data from the various flight-direction instruments and automatically calculates from them what the new course should be. The human pilot usually acts on five separate pieces of information, those provided by the gyro horizon, the directional gyro, the magnetic compass, the altimeter, and radio approach aid indicator. He must note these, and calculate from them how he should move the controls. The Zero Reader eliminates all these calculations and presents the result on a simple indicator, which shows to the pilot instantly and continuously whether he should fly right or left, or up or down.

Zero Readers are used in the 'Comet' aircraft. They increase the speed of the pilot's response, make his flying more accurate, and reduce his need for concentration, as he has to watch one instrument only. The Zero Reader brings the complete automatization still nearer.

Gyroscopes are now made in tens of thousands, though their development has been slow. The first attempt to use them for steering at sea

was made by Serson in 1744. Unfortunately the ship foundered, and he lost his life. Many later attempts did not succeed until the beginning of the twentieth century. Their failure was mainly due to the lack of adequate development in metallurgy and precision engineering. Materials which could withstand the enormous stresses in gyro rotors could not be reliably produced, nor could the requisite degrees of precision in manufacture be achieved by the methods previously available.

The orientating forces arising from the rotation of a mass of matter have been used by nature for directional purposes for at least fifty million years. The common house-fly and its distant ancestors have depended on a vibrating direction-indicating apparatus, consisting of rod-like weights in a drum of muscles, which is equivalent in its properties to a gyroscope. Spinning tops appear to have been invented by the Chinese.

The first major scientific application was made by Foucault in 1852, when he used the gyroscope to demonstrate the rotation of the earth, and in fact invented the word, deriving it from the Greek 'gyros' meaning 'revolution', and 'Skopien' meaning 'to view'. He predicted that it would be used in the future as a compass. But it did not prove practicable until after the invention and improvement of ball bearings and the electric motor, which enabled the rotor to run at very high speeds for long periods. The smoothness essential for satisfactory performance depended on the possibility of making the parts with very high precision.

Today, however, the gyro compass assists the navigation of the *Queen Elizabeth*. The automatic gyro-pilot relieves the fatigue of the human pilots of the transoceanic airliners, and helps them to concentrate on the safety of landing. The gyro compass helps the whaler in the Antarctic where the magnetic compass is greatly disturbed. The various gyroscopic instruments make for independence of weather conditions, and reliable services.

XVII

AIRCRAFT

JUST as the beginning of the nineteenth century saw the achievements of the railway and the steamship, so the beginning of the twentieth century has witnessed the conquest of the air. Aircraft are no sudden advances in man's struggle with nature, but rather the final yielding of defences which have withstood his attacks for a hundred years. From the time when the French physicist Charles in 1784 explained the action of Montgolfier's balloon, and constructed the first balloon to be filled with the light gas, hydrogen, one of the methods of aerial navigation merely awaited a motor. In 1852 Giffard, the inventor of the injector which bears his name, constructed a balloon fitted with a steam-engine and propeller, and succeeded in driving it at the rate of 5 or 6 miles an hour. In regard to another of the main problems, Cayley in 1809 stated the essential principles of aerial locomotion with a machine weighing more than the air it displaced.

Before passing to a consideration of the achievements of the last fifty years it will be convenient to glance briefly at the history of planes. Probably everyone is familiar with the way in which a kite is flown. When it is drawn through the air against the wind it rises, and will then go higher and higher as the string is paid out. There are now three forces acting on it:

(*a*) The weight which tends to make it fall.
(*b*) The pressure of the wind on its surface.
(*c*) The pull of the string.

As the force in the string and the weight of the kite act in a downward direction the wind tends to lift it. In fact, the wind can be regarded as having an effect in two directions, one tending to move the kite along in the direction of its own motion, and the other tending to lift the kite vertically. These two effects vary with the angle of the kite and speed of the wind. If the kite has not too heavy a tail the lower end gives before the wind and the kite rises. If the effective speed of the wind is increased by the boy who holds the string running against it, the

kite goes higher. If the boy runs with the wind the kite sinks lower and tends to fall.

Ever since kites have been flown it has been known that they are capable of raising considerable weights, and it was this fact that led to the proposal to drive a plane or thin sheet of material through the air with such a velocity that it would support a man. About 1871 Otto Lilienthal commenced to study the flights of birds—more particularly the position and shape of their wings—when gliding near the surface of water, and the construction of kites. Six or seven years later he constructed a frame carrying a pair of wings, and commenced to make gliding flights for the purpose of learning how to balance himself in the air. The wings of the machine were 27 ft. from tip to tip, and had an area of 100 sq. ft. By seizing the frame between the wings and launching himself from the top of a hill he was able to glide several hundred feet, and to alter his direction by swinging his legs. Three years later he constructed a glider with two planes one above the other in order to obtain greater lifting power. Lilienthal met with a fatal accident in 1896, and Percy Pilcher, who started similar experiments in England in 1895, was killed in the same way four years later.

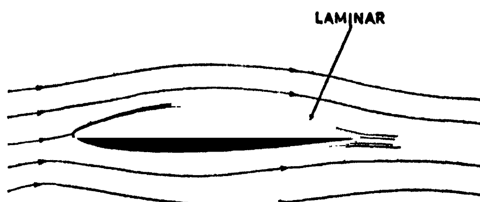
The evolution of the aeroplane on scientific lines was aided by the work of S. P. Langley of the Smithsonian Institution, Washington. He made a great number of experiments on the power necessary to drive a plane of given size through the air with given velocity, by fixing the planes at the end of a long rotating arm; and he followed this up by constructing models of gradually increasing size, and studying their flight when launched through the air. Having calculated exactly the power necessary, he succeeded in constructing a steam-engine which propelled the model for a minute and a half—the limit which the amount of fuel and water allowed.

Some time before 1900 gliding experiments with a biplane were made in America by the brothers Wilbur and Orville Wright. They increased the area of surface of 160 sq. ft. finally employed by Lilienthal to 305 sq. ft., and in 1901 succeeded in making flights more than 600 ft. long. They reduced the air resistance by lying flat on the lower plane instead of hanging from the framework as Lilienthal had done. In 1903 they constructed a motor and made flights lasting about a minute. The following year this was increased to over 5 minutes, and a year later to 38 minutes.

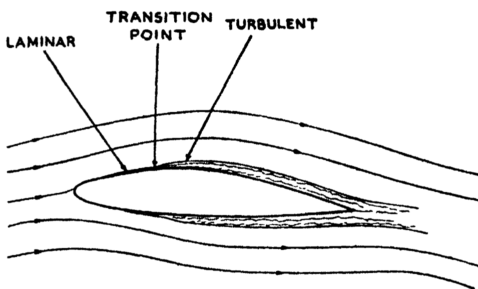
The progress of aeronautical science has been admirably reviewed by Sir Ben Lockspeiser, whom we shall now follow (Figs. 89–93).

Many years passed before the magnitude of the Wrights' achievement was fully understood. Their success was due to a sustained experimental attack on the problems of flight. They experimented with gliders, and, far more remarkable, they made extensive experimental

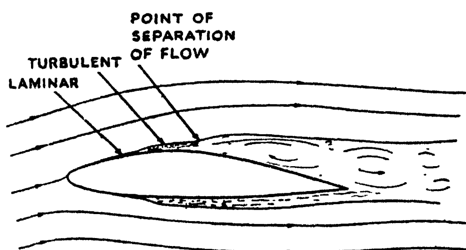
researches in aerodynamics. For this purpose they invented their own wind-tunnel. They determined experimentally the best sections of wings.



COMPLETELY LAMINAR BOUNDARY LAYER.



LAMINAR AND TURBULENT BOUNDARY LAYER



LAMINAR AND TURBULENT BOUNDARY LAYER FOLLOWED BY FLOW SEPARATION

Figure 89

They measured the forces acting on models of these wings in winds of various strengths, and the change in forces according to the inclination of the wing to the direction of the wind. They found the centres of

pressure of the model wings, under various speeds and directions of wind. These two young men were bicycle mechanics in an out-of-the-way small American town. Their development of research method in experimental aerodynamics, without tuition, by their own originality, is one of the most remarkable achievements in the history of engineering. They carried out their researches for many months, with accomplished scientific technique. Their observations were systematic, well-arranged, and thorough, and their diagrams and graphs first-class.

Through their method, they were able to investigate the problem of stability, and especially that of lateral stability, with their models in their wind-tunnel. They succeeded in finding a solution to the problem before they ventured themselves into the air in a power-driven machine. They invented a system of control that prevented side-slipping. This scientific achievement enabled them to survive, for most of their talented predecessors had been killed in accidents owing to the liability of their machines to side-slip.

Their grasp and mature mastery of scientific method was perhaps the most extraordinary part of their genius, but they were also gifted engineers. They succeeded in solving the problem of constructing a machine on the scientific data that they had collected. In addition, they designed and built an engine developing 20 h.p. and weighing only 240 lb., a very fine engineering achievement at the time.

The air resistance to an aircraft is called the drag. The work done in driving a machine is the product of the drag and the distance covered. As drag depends on the density of the air, and decreases as the density decreases, an aircraft needs the less power the higher the altitude at which it flies.

Drag is increased by fixed undercarriages, struts, wires, etc. The designer therefore tries to get rid of these. Besides these obvious sources of resistance, the shape of the aircraft is of fundamental importance. If the shape is correct, it will go through the air with the minimum of disturbance. The air will stream smoothly round it, and leave little wake. If the curves are not correctly 'streamlined', the streams of air will break away from the plane surface, and produce eddies and vortices, which have the effect of pulling the surfaces backwards, and increasing drag.

A large part of drag is due to the pressures on the aircraft surfaces, and the skin friction in the boundary layers on these surfaces. As the air passes over the wing, it flows evenly at first in the boundary layer near the surface. Its flow is then described as laminar. The boundary layer becomes thicker, until a transition point is reached, at which the layer breaks away from the surface and turbulence in the boundary layer commences. The aircraft designers try to arrange that the transition point is as far back as possible. Wings have been made where it does not occur until the air has flowed 60 per cent of the distance across the

wing. The solution of the problem is difficult. One condition is that the surface should be as smooth as writing paper, and there should be no waviness greater than one thousandth of an inch in a distance of two inches. One way of getting rid of turbulence in the boundary layer is to suck it inside the wing when it starts. Experiments show that the transition point might be moved back 75 per cent by this means. Unfortunately, however, the specks of dust and insects that are caught on wings

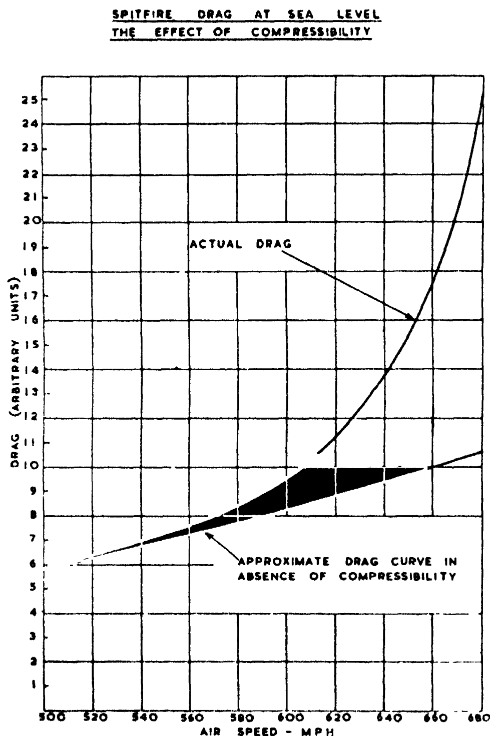


Figure 90

are often sufficient to cause the flow to break down from the laminar, streamline form into turbulence.

At very high speeds, another factor comes into consideration: the compressibility of the air. At speeds up to 500 m.p.h. the air behaves as if it were negligibly compressible. But at speeds approaching the velocity of sound (760 m.p.h. at sea-level) the drag of the aircraft due to air resistance increases very rapidly.

When the speed of the air relative to the surface of the wing is greater

than the velocity of sound in the same region of air, shock-waves are set up. These exert a force on the wing which greatly increases the drag. The formation of the shock-waves begins before the aircraft as a whole reaches the speed of sound, for the air flowing over the curved wings is accelerated owing to the shape, so its speed may exceed the velocity of sound before the wings themselves reach that speed. As the speed of the wing increases, the shock-wave exerts its pressure on the wing

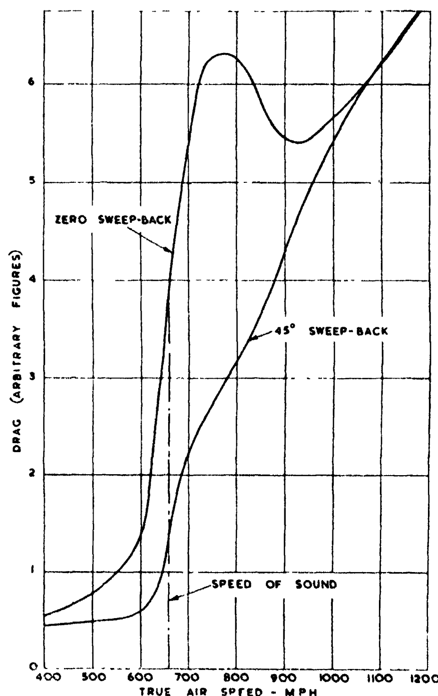


Figure 91. The effect of a sweep-back on drag at 40,000 ft.

further and further towards the back-edge. Hence the centre of pressure moves and the stability of the wing is affected. The shock-wave may also upset the control surfaces or flaps at the back-edge, so that the controls become ineffective.

These are some of the reasons why flying and the speed of sound is dangerous. When the aircraft as a whole reaches the velocity of sound, a shock-wave is formed on the bow, like that on a rifle bullet. Under these conditions the centre of pressure remains steady, even as the speed increases beyond the speed of sound. Thus flying at above the speed of

sound, even at enormous speeds, is relatively safe, once the aircraft has been safely accelerated through the velocity of sound region, i.e. has been safely brought through the 'sound-barrier'.

The speed of sound decreases with temperature, and hence with altitude. At the stratosphere it is 660 m.p.h. The ratio of the speed of the aircraft to the velocity of sound in the region of air through which it is flying is called the Mach number.

The onset of shock-waves can be delayed by suitable design of the shape of the wing cross-section. The thinner the wings, and slimmer the body, the higher the aircraft speed before shock-waves are formed. Thinness of the wing depends on the ratio of the thickness to the width in the line of motion. The Germans discovered that if the wings are swept back, the effective thickness-width ratio in the line of flight is much reduced at speeds of about the velocity of sound.

This is why the delta-shape has been adopted in such aircraft as the 'Vulcan'. It will be noticed, however, that at speeds of 1,000 m.p.h. and upwards sweep-back is of no advantage.

The compressibility of the air affects propeller blades in the same manner as aircraft wings. The rotational speed of the propeller edge, combined with the forward motion of the aircraft, begins to subject the propeller blade to increasing drag, at speeds of over 400 m.p.h. Below that speed, the propeller is very efficient, turning up to 85 per cent of the power of the engine into propulsive force. Over that speed, its efficiency falls off rapidly. Jet propulsion, in contrast, continues to rise in efficiency with speed. The effects are compared in Fig. 92.

In relation to compressibility effect, the propeller can hold its own up to 600 m.p.h., but in fact it is surpassed by the jet at a lower speed than this. The propeller disturbs the air-flow over the wings, and the piston engine is much heavier and bigger than a jet engine of equal power. The jet engine at present uses more fuel, so that jet aircraft are handicapped for very long flights. The advance of science will show how the efficiency of the jet engine can be increased. One direction will be from deeper knowledge of the behaviour of gases flowing through turbine blades under conditions of compressibility.

A jet engine takes in about 5 tons of air every minute. The aerodynamics of the flow of air through the engine is becoming as important as that of the flow over the wings and body. Turbulence in the engine is as serious as on the wings.

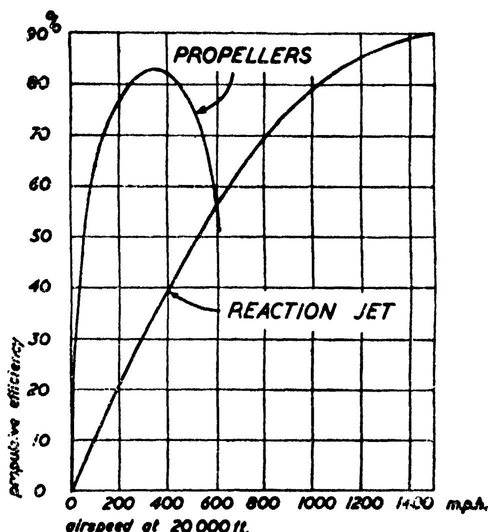
It is possible that higher working temperatures in turbines may become possible by cooling the blades internally by liquid or gas. Advances in metallurgy may lead to the production of alloys still more resistant to creep, the tendency of metals to slight but continuous change at high temperatures.

At very high speeds, two or three times the speed of sound, or say,

2,000 m.p.h., compressors for jet engines need not be necessary. The air rams itself into the engine, and creates its own compression. This leads to the ram-jet aircraft or 'flying pipe', for flying at very high speeds. At 2½ times the speed of sound the compression ratio for the flying pipe is already more than 8 to 1.

At low speeds the ram-jet is very inefficient, so auxiliary power would be necessary to accelerate such an aircraft up to speeds where it becomes efficient.

Aircraft may also be driven by rocket-motors, which do not depend



COMPARATIVE PROPULSIVE EFFICIENCIES

Figure 92

on the air for oxygen, but use fuel which already contains oxygen. The Germans made remarkable progress with these, using them in V2 rockets, and in the Me 163 interceptor-fighter. These engines are comparatively simple and cheap, and develop an enormous thrust for a small cross-section, up to 30,000 lb. or 15 tons per square foot. They also give a constant thrust, which is not affected by altitude, because it is not dependent on the air. They have, however, only about one-tenth of the efficiency of the jet engine. At present they are suitable only for assisting take-off of heavy aircraft, quicker interception, or any other sharp and short action.

The demands of aircraft construction have led to the production of

aluminium alloys with eight times the strength of pure aluminium, and three times as light as steel. Since the First World War, the strength has been almost doubled.

The production of alloys of such high tensile strength and lightness, which could also be easily worked, has assisted in a revolution in aircraft structures. This was the construction of the monoplane wing out of a metal skeleton, covered with a strongly stretched skin of metal

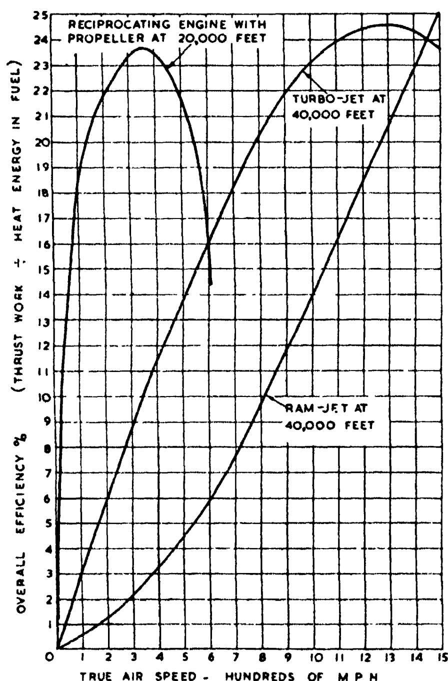


Figure 93

sheet, left in a permanent state of tension. This type of structure known as monocoque, is very light and strong, and resistant to deformation. The metal in the skin contributes much to the strength, and is not concerned only in providing a surface. As a surface, however, it is particularly good, being smooth, and much more resistant than fabric to damage and wear.

Magnesium alloys, especially zinc and zirconium, have been developed with great success for light castings, such as the cases of jet-engine compressors. Their strength-weight ratio is nearly 20 per cent greater than that of the best aluminium alloys. Besides great strength these magnesium alloys can be machined faster than any other metals used in engineering. Already about one-third of all aircraft castings are made of them.

The most serious drawback of magnesium and aluminium alloys is that they lose much strength with rise of temperature. Temperature-resisting alloys of titanium are now being developed. They are twice as strong as aluminium alloys for one and a half times the weight. At present they cost about £5 a lb., whereas aluminium alloys cost about 3*s*. a lb. But then, in the time of the Wrights, aluminium, besides being weak in strength, also cost £3 5*s*. a lb., yet by 1935 its price had been reduced to 1*s*. a lb. Perhaps methods of reducing the cost of extraction of this plentiful metal may be worked out, as they have been done for aluminium.

Stiffness of structure is becoming increasingly important as the speed of aircraft rises. Engineering structures such as aircraft wings and frames, and bridges, have a natural time of oscillation. If they are subject to stresses that start the frame vibrating, the vibrations may increase until the structure shatters itself to pieces. This kind of vibration in aircraft is called 'flutter'. The designer has to ensure that the speed at which 'flutter' is liable to develop in an aircraft is safely higher than the speed at which the machine will operate.

Another engineering problem of increasing importance is the fatigue which metals exhibit after continued use. A structure subject to repeated moderate stresses may, after a long time, suddenly break, the stress which causes the actual break being much smaller than those which the structure could easily resist when new. Much still remains to be learned about the cumulative effect of the strains caused by gusts on aircraft.

It is a striking fact that ever since 1910, the maximum speed of aircraft has risen at an ever-increasing rate. There is no obvious limit. High speeds, however, require great power and much fuel. Consequently, such aircraft are very heavy. The 'Comet' weighs 47 tons when fully laden, and 46 per cent of this consists of fuel.

Such aircraft require long strong runways. These are at present generally made of concrete. They are very bulky and expensive, besides destructive of agricultural land. By 1952, two million tons of concrete had already been laid at London Airport, sufficient to build a double-track concrete road from London to Edinburgh. Already, at this date, ten million pounds had been spent on construction.

The great French engineer Freyssinet has introduced pre-stressed concrete runway construction. Steel bars are laid in the concrete under

strong stress. These bars take up much of the strain from the landing wheels, and enable less concrete to be used.

The drawbacks of the concrete runway have led to the suggestion that runways should be laid on bags of water, so that they would give under the aircraft wheels, and distribute the pressure more evenly. The surface layer of concrete might then be much thinner.

The problem has directed attention to the development of the aircraft as a flying boat, which can land without wheels. In a big aircraft these may count for 6 per cent of the total weight. Yet another method is the development of 'belly-flop' landing on a big elastic sheet, like a huge blanket held out for persons to jump into, from a house on fire. The aerodrome problem is also directing more attention to the helicopter. A helicopter cruising at the moderate speed of 120 m.p.h. from the centre of London to the centre of Paris would be quicker than a journey by the fastest aircraft on the present routes from aerodromes outside London and Paris. As Sir Ben Lockspeiser has said, the future in the air may well lie in the conquest of the ground.

TYPICAL AEROPLANES

One of the earliest types of monoplanes was the 'Bleriot', whose designer was the first to fly across the Channel. It was made to carry one or two persons. The span of the wings from tip to tip was just under 30 ft. in the smaller machine and 36 ft. in the larger, and the lengths were 25 ft. 6 in. and 27 ft. 6 in. respectively. The areas of the main planes were 187 sq. ft. and 263 sq. ft. respectively. The single-seater had a lifting and the two-seater a fixed tail; the latter was therefore provided with elevators. The weights were 550 and 700 lb., and each was driven by a 50 h.p. Gnome engine. Just in front of the pilot's seat was fixed a lever which, moved to and fro in a fore-and-aft direction, warped the wings, and moved sideways governed the lifting tail or the elevator. The rudder was manipulated by a foot-rest.

The First World War gave an enormous stimulus to aircraft production, but as long as aeroplanes were required only for military purposes they had to be heavily engined, either for low-speed long-flight bombing, or high-speed, quick-moving fighting machines. They had to be capable of rising with the greatest rapidity from the ground, and of ascending to high altitudes in order to escape observation or be beyond the range of gun-fire. When hostilities came to an end some of the heavy bombing machines were converted into machines for carrying passengers and cargo; and when the Air Navigation Act was passed in 1919, Civil Aviation was at once accorded recognition and placed under regulation.

On 25th August 1919, the Air Transport and Travel Company began

a regular service between London and Paris, using DH4 machines fitted with Rolls-Royce engines. Within a few days Handley Page instituted a service on the same route, and on 25th September, a service between London and Brussels.

The heavily-engined bomber required 700 to 750 h.p. for its two passengers, while the commercial aeroplane of 1920 with two 450 h.p. Napier 'Lion' engines, carried 16 or 20 people. It did not rise so rapidly from the ground; its normal altitude was less than 5,000 ft., it had a normal speed of 115 to 130 and an average speed of 85 to 100 m.p.h. Moreover, while it answered quickly enough to the helm, it had none of the 'liveliness' which characterized the fighting machines during the war. The cabin was enclosed, provided with comfortable seats, and electrically heated.

A movement arose after the war to produce a small cheap machine for the 'owner-driver'. The first was the 'Avro Baby' which had a span of 25 ft., length of 17 ft., height of 7 ft. 7 in. It carried a 45 h.p. Green engine, 6 gallons of petrol and one gallon of oil. Its speed at the sea level was 80, at 10,000 ft. 71, and on landing 33 m.p.h.

In most respects the machines are operated in the same way as the earlier ones. Changes have been made, but they are in detail rather than in principle. Modern aeroplanes are constructed almost entirely of the light aluminium alloys and steel.

The engines have been continuously improved. Lightness has been secured firstly by making the crank cases of aluminium, instead of cast-iron. Subsequently aluminium alloy pistons with steel piston-heads to protect the more fusible metal from the action of the hot gases effected a further reduction in weight. Some engines have aluminium cylinders with steel liners in which the pistons run. One difficulty is to maintain the power at high altitudes where, owing to the low barometric pressure, the weight of air drawn into the cylinder at each suction stroke is smaller than at lower levels. A plan adopted to overcome this disadvantage is 'supercharging'. The engine does not draw air directly from the atmosphere, but receives it from a pump, which delivers it at approximately the sea-level pressures.

Of the flights before the First World War, those of the Wrights and of Bleriot were of outstanding significance. The first classic flight after the First World War was that of the crossing of the Atlantic. In 1919, Alcock and Brown went to Newfoundland with their machine, a Vickers-Vimy bombing machine, fitted with Rolls-Royce engines and hurriedly adapted for the purpose, to attempt the flight. Furnished with 865 gallons of petrol, sufficient for a journey of 2,440 miles, they left St. John's at 5.28 a.m. on 14th June, and landed at Clifden, Ireland, at 9.25 a.m. Allowing for the difference of longitude, the actual time of flying was 15 hours 57 minutes. For nearly 16 hours they had been

out of sight of land, often completely enveloped in fog, rarely able to see the sun, moon, or stars, and frequently unable to see the water below them. Half an hour after they started the wireless apparatus broke down so that they were unable to signal their position to any passing ship or to announce the imminence of their arrival. For four hours the machine had been encased in ice and when, finally, they made a nose-dive into a bog both aviators were dazed. But the task had been accomplished. The wide Atlantic had been crossed in one single flight, for the first time.

THE SPITFIRE

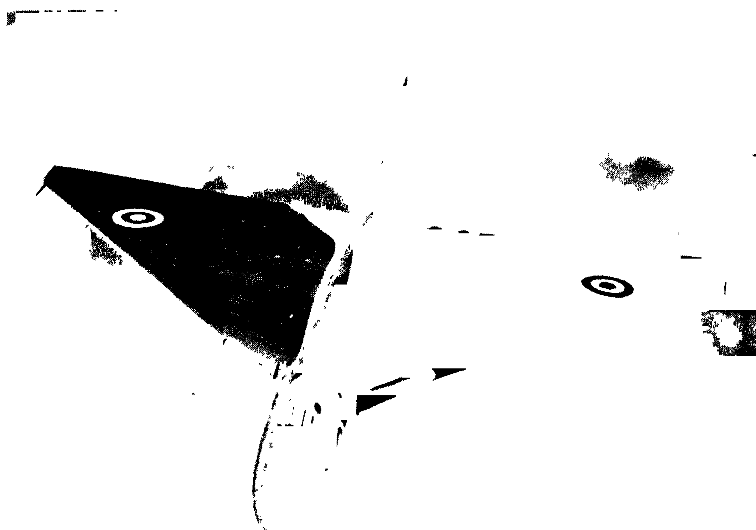
The 'Spitfire' fighter aircraft held a position of pre-eminence throughout the six years of the Second World War. It was the product of far-seeing inspiration in design, combined with an equal effort in engine development, and supported by effective engineering production.

Its immediate beginning can be traced to the seaplane race of August 1922 at Naples, for the International Schneider Trophy. It was won by the Supermarine 'Sea Lion', a biplane of complicated design, which had been lucky to win. It was evident that such a machine could not be expected to win the race of the following year. A radically new machine of 'clean' design would be needed, which followed the most advanced aerodynamical knowledge.

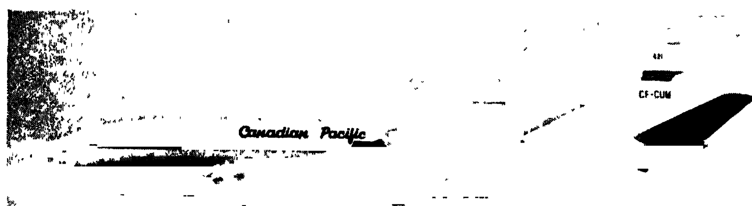
The chief designer of the Supermarine company was a young man, R. J. Mitchell, who was then twenty-seven years of age. He was convinced that the 'cleanest' possible design of monoplane was required, with cantilever wings, free from bracing wires and all unnecessary excrescences. It should be as small as could be built around a 700 h.p. engine, the best available in those days.

It did not prove possible to work out such a design for such a radically new machine quickly. But by March 1925, Mitchell and his staff had completed the design for the 1925 race. The machine was built by August, and in September set up a new world speed record of 226 m.p.h. This was the first time that a seaplane had beaten landplanes for the speed record. However, the machine did not compete in the race, for it crashed owing to the development of 'flutter'. Mitchell's confidence in the monoplane might have been shaken by this misfortune, but he retained his fundamental judgment.

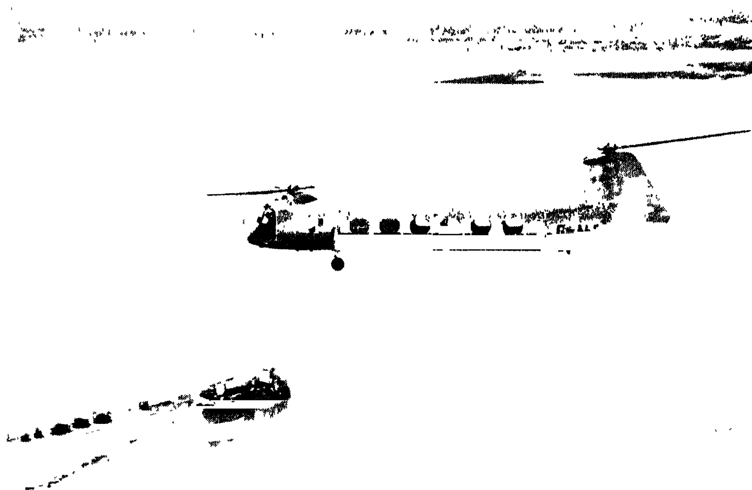
The S.4 was developed into the S.5 for the 1927 race. This had a metal fuselage, and wooden wings and floats like S.4. The radiators were built flush in the wings, and one float was used as the petrol tank, to balance the reaction from the propeller torque. This machine won the 1927 race at Venice, at a speed of 281·6 m.p.h. A speed record of 319·57 m.p.h. was put up by a similar machine later in the year.



LI*a*. Avro 'Vulcan' bomber



LI*b*. De Havilland 'Comet I' passenger liner



LII*a*. Bristol Type 173 helicopter



LII*b*. Flying bomb (V1) in flight

In the following S.6, Mitchell had the new Rolls-Royce engine R, the ancestor of the Merlin. It developed nearly twice the power of the Napier Lion. He placed the oil-tank in the fin, so that the slipstream from the propeller would cool it, and enable the area of the oil-cooler to be reduced. The S.6 won the 1929 race at 328·6 m.p.h., and shortly afterwards the same machine was used to set up a speed record of 357·7 m.p.h.

It was now necessary for Britain to win the Trophy only once more for it to become a British possession. In 1931, however, owing to the crisis of that year, the British Government indicated that they could not finance the Supermarine company's preparations for the contest. The late Lady Houston provided £100,000 from her private fortune to enable the preparations to proceed. Two S.6's were hastily improved, and each fitted with a special Rolls-Royce engine which could give 2,300 h.p., though only for a guaranteed duration of a few minutes. In order to keep the engine cool, radiators were placed on the top and bottom surfaces of the wings, and also on the floats. Even then, sufficient cooling was obtained only by allowing the coolant to boil away during the flight.

The Italians were making a determined effort to compete, but their engines completely broke down under comparable conditions, so they withdrew from the race. In order to win the race the improved S.6, the S.6B. had only to cruise round the course, without competition. This was done at 340·8 m.p.h. and the Schneider Trophy came to Britain permanently. On 29th September 1931, the aircraft was flown by Flight Lieutenant Stainforth at 407·5 m.p.h. over a measured course, so establishing a new world speed record.

With their experience of high-speed machines, the Supermarine company decided to submit a design for a fast, single-seat fighter, to meet a specification laid down by the Air Ministry. Mitchell attempted to meet this specification, and the result was the F7/30. It was a failure. He was still firmly convinced that his own basic conceptions were correct, and his firm allowed him to work out a design entirely according to his ideas of what such a fighter should be, though they had no contract. He produced drawings of a monoplane of a new standard of aerodynamic efficiency, far 'cleaner' than its predecessors, the F5/34. The undercarriage was to retract into the wings, and the cockpit was enclosed to give fuller protection to the pilot.

The wing was much smaller than in the F7/30, and yet it contained 82 gallons of fuel, and two machine-guns and their ammunition, besides the retracting undercarriage. Two more guns were mounted, which shot through the propeller disc by means of an interceptor system, and provision was made for carrying four small bombs under one of the wings. The Air Ministry decided to accept this design.

In 1934, under the inspiration of R. S. Sorley, it was decided that the new fighter should have eight machine-guns, all mounted in the wings, and to shoot clear of the propeller disc. This avoided the use of the interceptor gear, and of the slowing-down of the firing of the inner guns, which this entailed. With eight guns, the fast fighter would not only be able to overhaul the enemy, but to shoot him down within two seconds.

At this time, Rolls-Royce produced their PV-12 liquid-cooled twelve-cylinder engine, the prototype of the Merlin. Mitchell re-designed his machine around this outstanding new engine, incorporated eight guns in the wings, and many of the older tried features.

The fuselage of his latest design, F37/34, was still much like that of the Schneider trophy machines, but he now gave his wing its characteristic pointed ends, and made it exceptionally thin. It had been believed that the elliptically-shaped wing was more efficient than one which was straight-tapered, but the production problems of making such a wing had been considered impracticable. The construction engineers found however, that they should be able to manage it. F37/34 was now named the 'Spitfire', and the PV-12 engine the Merlin.

A full-sized wooden model, or 'mock-up', of the machine was built in the workshops in 1935, and construction of the prototype machine proceeded. It was the first British all-metal fighter, so it was slowly and very carefully constructed.

On 5th March 1936, it was flown for the first time, and it was at once evident that the 'Spitfire' was an outstanding machine. In June 1936, the Air Ministry placed a contract for 450, a very large order in those days. Production of the 'Spitfire' commenced. But Mitchell, whose health was not good, was already a sick man. He died in 1937, at the age of forty-two, and never saw the triumph of his masterpiece.

A good single-seater fighter should possess high speed. It should be able to climb very quickly, and operate at a great height. It should be easily manœuvrable, and carry heavy armament. The pilot should have a good view around him. The machine should be small and strong, easy to maintain, have a low landing speed, and a long range. In addition, its production should be as easy as possible. Mitchell's solution to this formidable combination of problems proved to be the best, and remained the best through the whole six years of the Second World War, a most remarkable achievement.

Mitchell adopted an all-metal stressed-skin design when stressed-skin, or monocoque construction, was relatively new. The large-scale production of such an advanced design provided great problems.

The wing consisted of a main spar, which, together with the skin, formed a box of immense torsional strength. The box also took much of the strains due to landing and to the recoil of the guns.

The main spar was built up of tubes which slid into each other, pro-

viding an almost solid root, consisting of five tubes. As the spar thinned towards the wing-tips, the inner tubes were progressively terminated, until only the two outer tubes remained. The tubes had to be a pushing fit, and yet had always to fit when picked at random. This presented difficult problems in control of quality in production.

In the 'Spitfire L.F.R. Mk. XIVe', the frontal area was contracted still further by using the frame of the engine itself as fuselage cross-bracing.

Such, in brief outline, was the most decisive single aircraft of the Second World War.

THE MOSQUITO

One of the most brilliant machines of the Second World War was the de Havilland 'Mosquito'. This was a twin-engined machine of very 'clean' design, powered with two Merlin engines. It was capable of a speed of 422 m.p.h., and long range, and could carry considerable loads (Plate L*b*).

The machine was designed in order to utilize the resources of the British furniture and wood-making industry for aircraft production. When the available supplies of aluminium were being fully used for the construction of metal aircraft, wood provided the available material for producing yet more aircraft. The skilled workers of the furniture-making industry could, by using this material, be mobilized for aircraft construction.

The 'Mosquito' was, accordingly, made mainly of wood. It trusted to its great speed for safety from attack. The two Merlin engines gave it this speed, and consequently it was able to perform remarkable reconnaissance and special flights, and even was used for dropping one-ton bombs on Berlin twice nightly.

The 'Mosquito' accomplished its aims magnificently, in utilizing skill and raw material not otherwise mobilized for aircraft construction, but the inherent difficulties of using wood prevented this kind of construction from being adopted permanently.

THE VULCAN

This four jet-engined delta- or triangular-shaped bomber was first flown on 30th August 1952. It was produced by the Avro section of the Hawker-Siddeley Group. Sir Roy Dobson, the chief of the Avro section, said that it was the result of a programme of research, design and development which started in 1947. They had arrived at the triangular-shaped wing, as the natural outcome of aerodynamical development, and it would remain in use for some time to come. It is simple in construction, very stiff and strong, and has excellent aerodynamical

characteristics. Its properties are among the most advanced among existing design for bombers and transport aircraft (Plate LI*a*).

Its lines are very 'clean'. It has a large wing-area, and consequently low wing-loading, and is easily controlled at all speeds. It does not require slots or flaps for giving high lift. The elimination of these moving parts is a gain in servicing, freedom from liability to breakdown, and simplicity in production. It was claimed in 1952 that the 'Vulcan' flew faster, higher and further with a big load more economically than any other machine.

THE COMET

The introduction in 1952 of the 'Comet' four jet-engined transport aircraft on some of the main air routes began a new stage in air transport (Plate LI*b*), even though the original fuselage design has proved unsatisfactory.

The British aircraft industry decided not to engage in mass-production of big piston-engined machines after the end of the Second World War, but to concentrate on the solution of the problems of the aircraft of the next generation: the jet-engined aircraft. This policy has proved on the whole successful.

The 'Comet' was conceived in 1946 and first flown in 1949. It inaugurated the first jet passenger services on 2nd May 1952.

The Series I 'Comets' have four de Havilland Ghost engines, and the Series II four Rolls-Royce Avon jet engines.

Internally, the cabin contains either 36 or 44 seats, and carries 12,500 lb. and 13,500 lb. pay-loads respectively. The aircraft fly in stages of 1,500–2,500 miles.

They are 93 ft. long and 115 ft. in span, and have a sweep-back of 20°. The maximum landing weight is 80,000 lb. Their cruising speed is 500 m.p.h., and operating altitude 35,000–42,000 ft.

The wing-loading is moderate, and the stalling speed modest. Owing to the simplicity of the jet engine the cockpit instrumentation is remarkably simplified. The aircraft has an operational crew of four and two stewards. The flying controls are operated by duplicated hydraulic boosters, with a power supply from two engine-driven pumps. A secondary system of hydraulics operates the flaps, air-brakes, undercarriage retraction, nose-wheel steering and wheel-brakes. All fuel is carried in the wings.

The cockpit, cabin and luggage cabins are pressurized to 8¼ lb. per sq. in., so that when the aircraft is flying at 40,000 ft., the cabin pressure is equivalent to that in the atmosphere at 8,000 ft. Fresh warm air is taken from the compressors of the four engines. Serious accidents have however shown that stronger fuselage construction is necessary.

The mountings of the engines are specially designed for quick changing. A complete engine can be changed from cowl-up to cowl-up by three men in one hour.

THE HELICOPTER

The principle of the helicopter is one of the oldest that has been pursued in the conquest of the air, but the technical difficulties which have to be overcome in making it practical are very great. It is necessary to have a revolving system which develops sufficient lift to hold the machine, with its engine and load, in a hovering position. Attempts to hold up engines by means of ordinary propellers failed. The first to find a satisfactory solution of the problem was the Spanish engineer Juan de la Cierva, who was unfortunately killed in an airliner crash in 1936, at the age of forty-one. Cierva showed how large revolving blades, combining the properties of propeller blades and rotating aircraft wings, could be controlled by variations of pitch and speed in such a way that the aircraft rose, hovered, flew horizontally, and performed all the necessary motions of a manœuvrable aircraft. The advance of aerodynamics made the analysis of the forces better understood, and the advance of metallurgy and engineering enabled rotors of the correct aerodynamical design to be made sufficiently strong to withstand the stresses, and an engine with a sufficiently low weight/power ratio.

A small light helicopter developed from Cierva's machine is the Saunders-Roe 'Skeeter'.

This machine is a two-seater with a single main motor for lift, and an auxiliary motor in the tail for compensating torque, and giving directional control. The engine is a Blackburn Cirrus, which drives the rotors through a mechanical transmission system. A primary gear-box is mounted on the starboard end of the engine, which incorporates rotor-engaging and free-wheel clutches, and is connected with a short intermediate shaft to a secondary gear-box carrying the main motor-shaft. The tail motor is driven from the secondary gear-box through shafting and level gear-boxes. The main rotor consists of three twisted blades, each of constant chord. These can be folded parallel to the rear fuselage.

The top speed at sea-level is 115 m.p.h. The operational ceiling is 13,000 ft., and the hovering ceiling 3,300 ft. It runs for 3 hours at 86 m.p.h. The operational weight is 1,476 lb. The rotors weigh 211 lb., the power unit 482 lb. and the structure 280 lb.

The machine is designed for personal transport, air-mail, crop-spraying, traffic control, surveying and photography, message and supply dropping in difficult situations, etc.

The Bristol Aeroplane Company have produced a helicopter for service with the R.A.F. Coastal Command.

Helicopters are also being developed for transport of many passengers. The 'Bristol' type 173 is an example. It has two large rotors (Plate LII*a*).

Work is also in progress for the development of the convertible machine, one which has the properties of the helicopter for starting and hovering, and can be converted in the air into a fixed-wing machine, with the advantage of speed which this brings. Various degrees of convertibility may be arranged. The pilot can, as it were, switch in for a helicopter or a conventional aircraft, as he wishes.

In addition to these developments, much research is in progress on the utilization of the jet engine for providing the power for helicopters.

THE FLYING BOMB

The V1 flying bomb introduced by the Germans near the end of the Second World War is an ingenious contrivance. It is a small automatic aeroplane 25·3 ft. long, made almost entirely of thin welded mild-steel plate, and driven by a jet-reaction engine of extremely simple design. The total weight is 4,750 lb. and the flying speed 360 m.p.h. The engine develops a thrust of 600 lb. (Plate LII*b*).

The engine consists of a tube 11·25 ft. long, with a maximum diameter of 1·9 ft., built of steel plate. On the inside, near the front end, is a grid bearing a number of flap-valves, which are the only moving parts. Nine fuel tubes project from the grid into three Venturi mixing chambers formed by four louvre bars. The fuel tanks have openings of $\frac{1}{16}$ in. The grid consists of castings incorporating flap-valves, which contain 126 double rectangular leaves of very thin steel. Their inner edges are designed to press together, so that they form non-return valves. When there is high pressure in the combustion chamber they automatically close, but otherwise easily blow open when air rushes on them from outside.

The three nozzles above the top row of fuel jets are used when the engine is being started before launching. They receive a supply of compressed air, which is injected into the combustion engine before launching. A sparking plug is fixed in the top of the combustion chamber, about $2\frac{1}{2}$ ft. from the front. This is used to start the engine. When it is going, the current for the plug, and the compressed air supply, are disconnected.

The plane is flung into the air by a catapult at a speed sufficient for the engine to sustain its run operation. Suppose the engine is in flight at full speed, and the valves are closed by the high pressure of gas in the combustion chamber, due to the burning of the fuel and air mixture.

The pressure forces the burning mass of gas backward down the pipe, and it issues as a jet, causing the engine, and hence the plane, to go forward by reaction.

When the pressure in the combustion chamber falls sufficiently, owing to the escape of the gases in the jet, the air pressing on the outside of the grid, owing to the plane's rushing flight, is able to force the flap-valves open and stream into the combustion chamber. Fuel is pumped in at the same time, so a fresh explosive charge is produced, and ignited at the proper moment. A cycle of explosions is set going, at the rate of about 45 per second or 2,700 per minute. The succession of spurting jets produces an average thrust about equal to that of a 725-h.p. propeller aircraft piston engine. It consumes about one gallon of petrol every ten seconds, i.e. about the same as a 6,000 h.p. Lancaster bomber. The engine is therefore thermally very inefficient.

The plane is guided by an automatic pilot consisting of three gyroscopes, driven by compressed air. The master gyro controls the rudder and elevator through air-driven servo systems, and the two secondary gyros damp out oscillations. The master gyro is helped to retain the steady direction of its axis by a magnetic compass. The height at which the plane flies is set by the automatic pilot mechanism.

In the tip of the nose is a little windmill. This is turned by the air to unwind a counter. When the counter is unwound to zero, the plane is thrown into a steep dive. This cuts off the flow of petrol to the engine, which abruptly stops. The charge in the head explodes on hitting the ground or obstacle.

The plane is made in the cheapest and simplest way, and the engine not to last much longer than the few minutes of flight. It could be turned out inexpensively in large quantities by mass production.

MODERN ROCKETS

London was startled in 1944 by loud explosions followed, and not preceded, by roaring noises. These were due to the V2 rockets. They were one of the results of a programme of rocket development begun in 1929. The first successful rocket of the V2 type flew 170 kilometres, in 1942.

The V2 is about 46 ft. long, and 5 ft. 6 in. in diameter. Its weight when launched is 12·5 tons, of which more than two-thirds is fuel. The explosive charge weighs nearly one ton (Plate LIII*a*).

The power unit consists of a combustion chamber, with a neck and expanding exhaust, to form a Venturi tube. Intense combustion is kept up in the chamber, so that gases speed out through the neck, and increase their speed by expansion in the throat, issuing in a jet with tremendous momentum.

The diameter of the chamber is about 3·11 ft., the throat 1·32 ft. and the exit 2·41 ft. The pressure in the chamber is about 294 lb. per sq. in. and the temperature 3,000° C. The gases pass at the speed of sound through the throat, and pass out at about 7,000 ft. per sec. in the exhaust jet.

Fuel in the form of alcohol and liquid oxygen is drawn from two tanks, by an auxiliary pumping system driven by a steam turbine developing about 550 h.p. The steam for driving the turbine is made by mixing hydrogen peroxide and permanganate under pressure. It issues into the turbine at a temperature of 420° C. and 350 lb. pressure.

The alcohol and the liquid oxygen are driven by the turbine through eighteen mixing burner cups in the base of the combustion chamber.

The rocket is fired vertically. The thrust increases gradually, so the rocket leaves the ground without shock. The thrust rises to about 28 tons. The fuel from the main tanks is used up in about one minute, by which time the rocket rises to a height of about 22 miles. The rocket is steered by an automatic gyroscopic pilot which operates fins made of graphite, in the interior of the jet. The pilot gradually steers the rocket until it is inclined at 45° to the horizontal. The range is fixed by estimating the speed of the rocket, and cutting the engine off at an appropriate moment. This was done by radio control from the ground, which could operate radio equipment in the rocket.

The maximum velocity is about 5,000 ft. per sec. or 3,400 m.p.h. and the range about 180 miles. Just before the burning stage is ended, the V2 thrust is about 70,000 lb., and its engine is developing about 750,000 h.p.

As the rocket falls with a velocity far exceeding that of sound, its approach cannot be heard. The roar that succeeds it is the sound of its rushing through the air. The sound of the rushing arrives after the arrival of the rocket itself.

The late W. G. A. Perring, whose account of V2 has been followed, has made some speculations on future possibilities. Suppose the explosive charge is removed, and the space fitted with a pressure chamber containing a human pilot. Also, the rocket is fitted with small wings.

Suppose, now, that this rocket is then carried by a booster rocket up to a height of 80,000 ft. and released at a speed of 3,000 m.p.h. The human pilot will now start up his engine, which has been re-designed to give a thrust equivalent to 1,640 m.p.h. in level flight at 80,000 ft. First of all, the addition of the wings will have increased the range of the ordinary V2 from 180 to 350 miles. The second arrangement, with the booster rocket, might raise the range up from 1,500 to 3,000 miles. Such a rocket could complete the journey from London to New York in less than one hour.

Remarkable as these prospects are, they do not contemplate speeds of

more than 8,000 m.p.h. In order to escape from the earth's gravitational field, a speed of 24,000 m.p.h. is necessary. So a good deal more development must be achieved before it is possible to visit the moon. The scale of performance already achieved is, however, not quite outside that which will be required to explore the spaces between the planets and the stars.

XVIII

RADIO AND RADAR

THOUGH one or more means of transmitting messages by electricity have been known now for a century, the mechanisms by which they are accomplished are understood only by those who take a general interest in physical science, and the few to whom electrical communication is a profession. Electricity and magnetism operate across apparently empty space, and the links which connect cause and effect have to be pictured and supplied by imagination.

Before Marconi, Lodge and Preece both succeeded, independently, in transmitting messages between two stations quite unconnected by wires; but they employed the induction currents discovered by Michael Faraday in 1832. As long ago as 1888 Hertz had succeeded in producing and examining the properties of electric waves, but their interest for investigators lay rather in their similarity to waves of light than in their use as a means of communication. The idea of wireless as radio communication was first carried out practically by Marconi, who came to England and laid his plans before Preece, from whom he received no little encouragement and assistance.

Soon after Marconi applied for his British Patent in 1896, signals were sent across Salisbury Plain over 1¾ miles. Next year the distance was increased to 4 miles in March, 8 miles in May, 10 miles in July, 14½ miles in November, and 18 miles in December. During the naval manœuvres in July, 1899, messages were exchanged between three vessels up to 85 miles apart, and in August signals were transmitted across the Channel. By 1901 the distance at which signals were possible had risen to 1,800 miles. The two stations were St. John's, Newfoundland, and Poldhu in Cornwall. The vast stretch of space between England and America had been bridged.

Before proceeding to examine the methods by which in such an incredibly short time it has been possible to link up every country in the world by radio it will be profitable to consider what wave motion is, and to review the manner in which electric waves can be produced.

WAVE MOTION

When a stone is dropped into still water little ripples spread over the surface in ever-expanding circles, and communicate to any small floating object in the vicinity a vibrating motion about its position of rest. The water itself does not move with the ripple, and there is no appreciable tendency for the floating object to be translated in any direction—not even in that taken by the waves. As the stone reaches the surface it first makes a depression, then forces the water out of the way and breaks through. After it has disappeared, the water returns inward and upward to its former position with a swing, and even becomes heaped up where it was originally depressed. This swing is repeated a number of times, but to a gradually decreasing extent, and the ripples become smaller and smaller until they cease to be formed at all. Further, as each ripple spreads out from the centre of disturbance it gets fainter and fainter until it fades away.

This method of producing ripples is accompanied by a splash, and a good deal of the energy of the falling stone which might go to form waves is thus wasted. A more effective method is to float a small block of wood—a wooden ball, for example—and then to tap it slightly with a hammer. There is here no splash, and nearly the whole energy of the vibrating ball is utilized in forming waves.

The waves produced by both these methods are in short trains, each consisting of a few vibrations which soon die away. They can, however, be made continuous if the ball is lightly tapped every time it rises to its highest point. Each ripple then may be as large as, and may even become more powerful than, its predecessor, and a persistent stream of uniform ripples will extend over the surface of the water.

These waves consist of alternate crests and depressions or troughs, and the distance from crest to crest or trough to trough is called one wavelength. It represents the distance the wave travels while the object which caused it makes one complete vibration. If the object makes 10 vibrations a second, then 10 waves will be produced per second, and the first wave will have travelled 10 times the wave-length in one second. Or if N is the number of vibrations per second, L is the wave-length, and V is the velocity of the wave, then

$$V = N \times L$$

The experiments described show waves along the surface of the water only; but if the vibrating body were immersed in a block of jelly the waves would spread out in all directions and not merely in one plane. The reader who is familiar with the way in which sound is propagated will have no difficulty in realizing how a disturbance can cause waves to extend outwards, not in circles, but in spheres or other solid shapes

depending on the shape of the vibrating body. The medium, however, in which electric waves are produced is not water, nor air, nor any kind of matter as we know it. They can be produced in, and will travel through, a vessel which has been deprived of its air by the most powerful and effective pumps yet constructed. But inasmuch as they are modified considerably by the matter—air, water, earth—through which they pass, it cannot be said that matter is not concerned in their transmission.

THE PRODUCTION AND TRANSMISSION OF ELECTRIC WAVES

An electric wave requires for its source an electrical vibration, and this was obtained by Marconi in the following way. In Fig. 94, a battery or dynamo supplies current to the primary wire of an induction coil or transformer.[1] The secondary coil of the transformer has one end connected to the aerial wire (a long wire suspended from a tall mast), which terminates in a small knob, and the other end connected to a

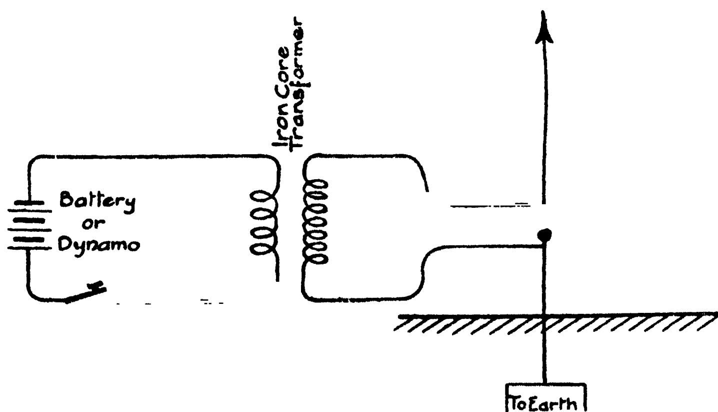


Figure 94. Transformer, spark gap, and earthed aerial

similar knob below. When the operator closes the switch the current flows round the primary circuit, and tends to include a similar current in that connected to the aerial. Electricity may be regarded as running into the aerial and the earth, until the former can hold no more, when a discharge takes place between the knobs and the current flows down to earth. When the switch is opened the stoppage of the current in the primary causes a similar momentary current in the secondary, but in the opposite direction.

[1] For an explanation of a transformer, see Chapter V.

Under proper conditions the spark discharge is oscillatory, the electricity rushing backwards and forwards from one end of the wire to the other many times a second. Each spark discharge, therefore, is accompanied by a short train of waves produced by the to-and-fro motion of the current in the wire. This may be illustrated by considering a rope, one end of which is held in the hand and the other attached to a point so far away that the rope is fairly straight. If now the end held in the hand be moved up and down smartly a few times a wave will travel along the rope. The rope then represents a direction in which a wave can be sent, while the movement up and down of the hand represents the upward and downward flow of the current in the aerial wire. The *earthed* aerial represents the essential feature of Marconi's original invention.

If the switch is replaced by a Morse tapper—a lever for making and breaking contact, and the coil is worked continuously by a trembler

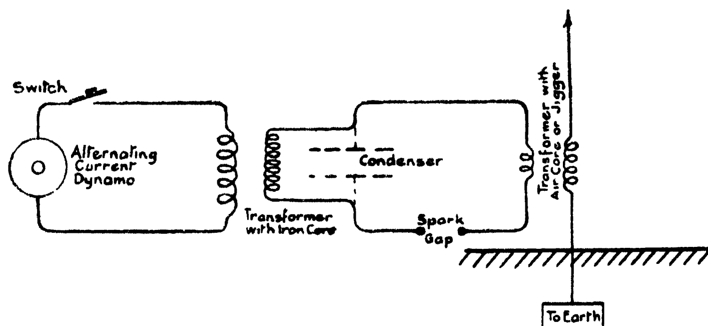


Figure 95. Transmitting aerial with coupled circuits

such as is used on an ordinary induction coil, then the emission of waves can be broken up into 'dots and dashes' and signals sent in the Morse Code. For though each spark only produces a short train of waves, yet with 200 or more sparks per second and fifty or more waves per spark, there will always be some waves radiating from the aerial. That is to say, the duration of contact even for a Morse dot is so long that it cannot be completed in the interval between the death of one train of waves and the birth of the next.

Unfortunately, this delightfully simple arrangement is similar to the splash method of sending out water waves, and is not very effective over long distances. A large amount of energy is wasted in the spark, and a series of violent impulses or splashes is obtained instead of a persistent, penetrating wave motion such as is desired. It was accordingly replaced by the apparatus shown diagrammatically in Fig. 95. The alternating current is supplied by a dynamo to a transformer,

which increases the electromotive force to a considerable extent. The primary circuit may therefore be regarded merely as providing a suitable supply of electricity. The secondary circuit, in which for the moment the dotted lines showing the condenser may be disregarded, consists of two coils and a spark gap. The left-hand coil belongs to the transformer, and every time the current given by the alternator reverses its direction a current in the opposite direction is induced in this coil. The flow of this current produces a spark across the gap and, flowing through the right-hand coil, induces a current in the aerial coil which is wound on the same axis.

The condenser, shown in dotted lines, consists of a series of metal plates separated by air or paraffin. The even numbers are connected with one wire—say the lower in the diagram, and the odd numbers to the other. They are thus equivalent to one pair of plates of many times the area. Their purpose is to absorb electricity until sufficient has accumulated to make a powerful spark across the gap; in other words, the condenser increases the *capacity* of the circuit.

One other important property of these circuits and the aerial must be mentioned. They all have the same natural frequency. When an electrical discharge completes a circuit as at the spark gap in Fig. 95, there is a natural period of oscillation which depends on the form and dimensions of the circuit and the size of the condenser, and this period of oscillation can be varied by altering any one of these factors. To illustrate this, suppose the U tube shown on page 55 to be filled with water, and the level in one limb to be first depressed by blowing into the end of the tube and then released, the water will swing backwards and forwards, occupying a time for each oscillation which depends on the form and dimension of the tube and the quantity of water in it. To go back to the 'coupled circuits' in Fig. 95, the dynamo will produce alternating current of a certain definite period, and the circuits and the aerial are arranged to have the same natural period. They are then said to be in 'syntony' or to be in tune with one another. The period of vibration of any circuit is usually altered by varying the effective size of the condenser—cutting part of it out of action—and the operation is called 'tuning'. The methods of securing syntony were worked out mainly by Lodge, and the Lodge-Muirhead patents were acquired by the Marconi Company.

THE DETECTION OF ELECTRIC WAVES

Sending signals across space is not of much value unless means can be devised of detecting and interpreting them at their destination, so we now proceed to examine the instruments at the receiving station. Marconi's first detector was a device due to Branly, who discovered that

metal filings in a small heap rested so lightly on one another that they offered considerable resistance to the passage of electricity, and a weak current was unable to flow through them. When, however, an electric wave fell upon them they became conducting, but shaking them up rendered them non-conducting again. On the supposition that the wave caused the particles to cohere and make continuous metallic contact, the device was called a coherer. In its original form it consisted of a heap of filings between the ends of two metal rods enclosed in a glass tube. The rods and filings formed part of a circuit containing also a battery and electric bell as in Fig. 96. When the wave fell on the coherer the current passed and the bell rang. Unless means were taken to prevent it, the bell continued to ring so long as the filings allowed the current

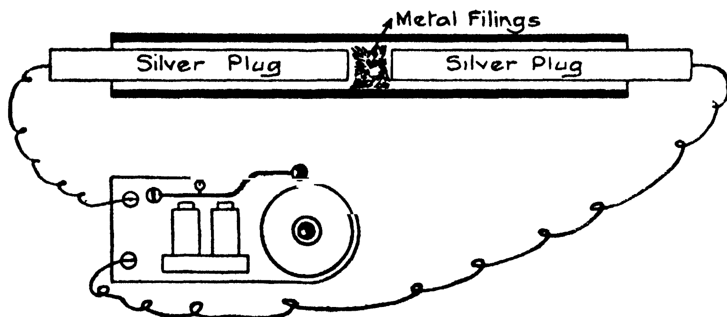


Figure 96. Branly coherer and bell—the latter is drawn to a smaller scale

to pass, so that even if the waves stopped the observer would not know it. To obviate this the hammer of the bell was so arranged as to strike the tube containing the filings, which were thus de-cohered and prepared to receive another signal. At the same time the gong of the bell was removed and the signals received through a telephone, Morse tapper, or any of the usual telegraphic receiving instruments. The use of the coherer, then, was to put into operation a local battery and telephonic or telegraphic receiving set, and it did this in accordance with the movements of a Morse sounder or tapper at the sending station.

The coherer was replaced in 1901 by the magnetic detector, an ingenious contrivance whereby the extremely feeble currents produced in an aerial at the receiving station were used to operate a telephone.

Another type of detector consists of a crystal or crystalline substance placed in the circuit through which small currents induced by that in the receiving aerial will pass. Silicon or carborundum is used for the

purpose. A diagram of a typical arrangement is shown in Fig. 97. The aerial on the left hand is connected to earth through a coil which is wound on the same axis as another coil in the telephone circuit. The telephone circuit contains a battery and the detector, and there are two condensers, one on each side of the detector. The circuits are tuned so as to be in syntony with the aerial. When a train of waves of the right frequency strikes the aerial, currents are induced in the first portion of the circuit and charge up the first condenser. This tends to overflow through the detector, which allows the second condenser to become charged, but does not permit the charge to pass out again. It acts as a trap, permitting the current to flow one way but not another. The second condenser therefore discharges steadily through the telephone, but at such a rate that the detector is enabled to pass to it several charges

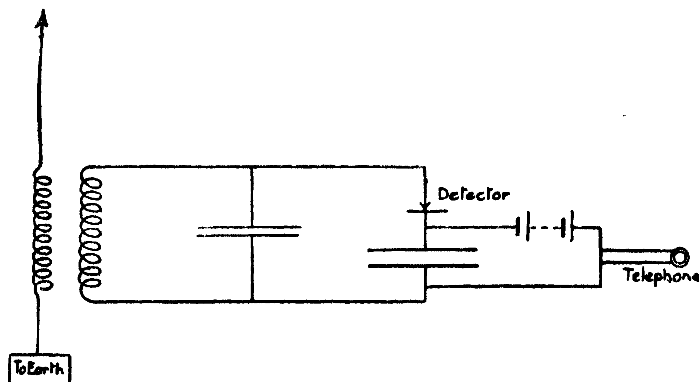
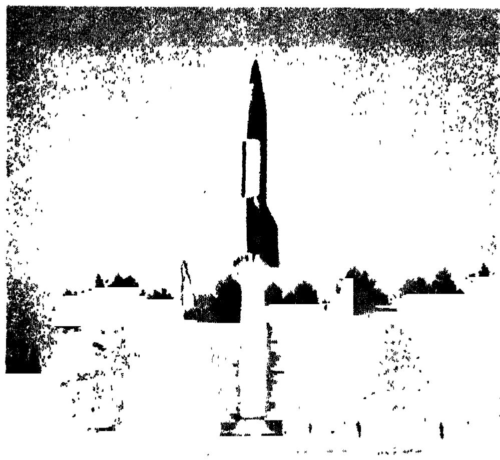


Figure 97. Receiving aerial with coupled circuits

before the first one has escaped. Detectors of this kind are called integrating detectors, because they sum up or add together a number of small impulses.

Aerials behave like tuning forks. If one is oscillating at a certain rate it is sending out waves of a corresponding length, because, as was shown on page 347, the wavelength is equal to 186,000 miles divided by the number of vibrations per second. These waves can be picked up most easily by an aerial having the same natural period of vibration and capable itself of radiating waves of the same length. Since the natural period of a circuit can easily be altered by altering the capacity, any circuit can be tuned so as to be in syntony with another circuit. It is clear that if every message was picked up by every receiving station there would be great confusion, and on that account each station has a fixed wavelength for transmitting which is known to all the other stations. If a signal reaches a station which is not in proper tune with



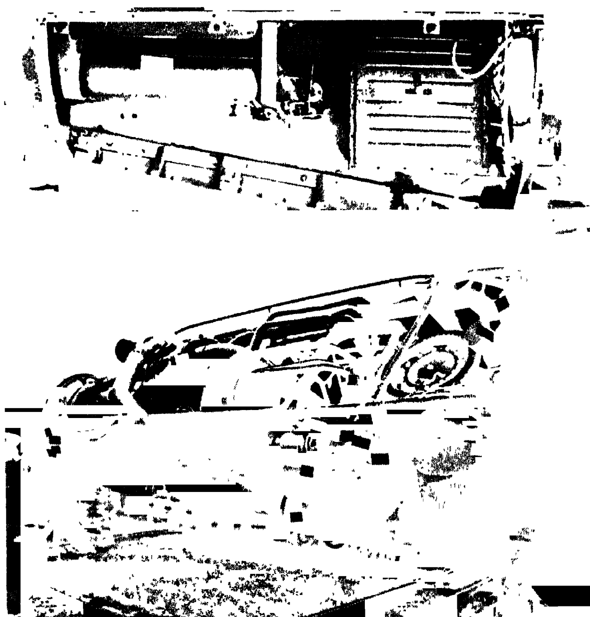
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LIII*a*. Rocket bomb (V2) being launched



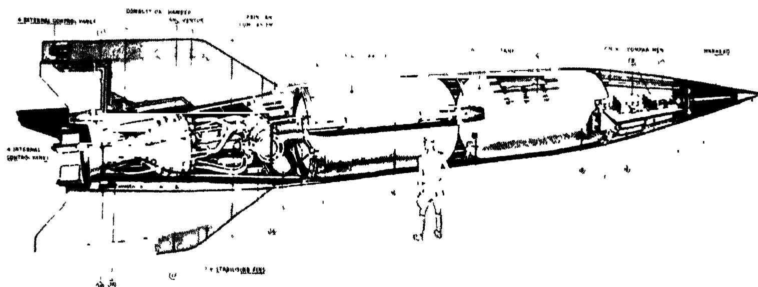
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LIII*b*. Nose compartment of V2, showing control gear



(Crown Copyright)

LIII*c*. Tail compartment of V2, showing motors

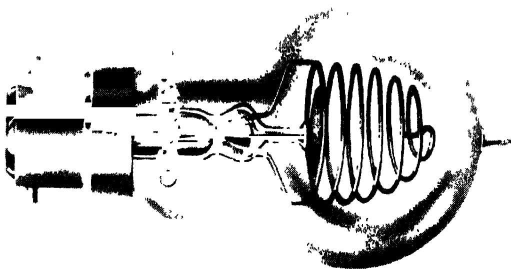


(Crown Copyright)

LIV*a*. Dissected drawing of a V2

The drawn figure gives an idea of the size of the weapon, which is approximately 46 ft. long and 5 ft. 6 in in diameter Key to annotations

(1) Chain drive to external control vanes (2) Electric motor (3) Burner cups (4) Alcohol supply from pump. (5) Air bottles. (6) Rear joint ring and strong point for transport (7) Servo-operated alcohol outlet valve (8) Rocket shell construction (9) Radio equipment (10) Pipe leading from alcohol tank to warhead (11) Nose probably fitted with nose switch, or other device for operating warhead fuse (12) Conduit carrying wires to nose of warhead (13) Control exploder tube (14) Electric fuse for warhead (15) Plywood frame (16) Nitrogen bottles (17) Front joint ring and strong point for transport (18) Pitch and azimuth gyros (19) Alcohol filling point. (20) Double walled alcohol delivery pipe to pump (21) Oxygen filling point. (22) Concertina connections (23) Hydrogen peroxide tank (24) Tubular frame holding turbine and pump assembly. (25) Permanganate tank (gas generator unit behind this tank) (26) Oxygen distributor from pump (27) Alcohol pipes for subsidiary cooling (28) Alcohol inlet to double wall (29) Electro-hydraulic servo-motors.



LIV*b*. A neon lamp

it, the operator alters the capacity of his aerial until the sounds in the telephone or loud-speaker reach their greatest distinctness.

THE GROWTH AND APPLICATIONS OF RADIO

The problem of sending messages over long distances was facilitated by Marconi's invention of the *directional* aerial in 1905. He found that a horizontally bent aerial would radiate waves most strongly in a direction opposite to the free end.

While communication across the Atlantic has been maintained regularly now for more than fifty years, it must not be imagined that there are no difficulties and that all the problems have been solved. In spite of a high degree of perfection in the instruments for producing electrical waves and in those used to detect them, the wave meets with many adventures on its way. One of the problems which, while it had been surmounted practically, long evaded theoretical explanation, is the particular path pursued by the wave between the stations. When Marconi first made the attempt to put England and the American

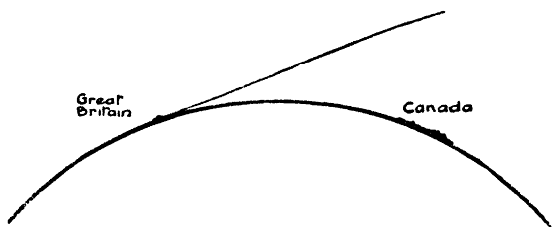


Figure 98. The Atlantic Hump

continent into communication, there were no scientific facts which pointed to success, but there were some which indicated the impossibility of surmounting the great aqueous hump of the Atlantic, 125 miles high, which lies between (Fig. 98). An electric wave is in effect a very long light wave travelling with the same velocity—186,000 miles a second—and possessing many other similar characteristics. Now light waves show a rooted objection to turning a corner. Save for a slight bending round the edges of objects, they pursue a straight path from origin to destination. If an electrical wave were endowed with equal rectitude, and were launched on its way to Canada from Poldhu, it would arrive there something like a thousand miles above the land. Signals hovering in the heavens above and having no tangible connection with the earth below would be rather useless; from that height they could not even be collected by a kite. Fortunately, however, the

waves come to earth themselves. They are reflected down by the ionized Heaviside layer in the upper atmosphere.

There are a number of kinds of interference which arise from electrical disturbances in the earth's atmosphere. A flash of lightning is liable to give rise to a wave of enormous power which will set half the aerials on the earth vibrating in spite of the differences of pitch to which they are tuned. Thunderstorms are at their worst in the summer in temperate latitudes, but they occur to some extent all the year round, and those in the tropics are of extreme violence. They produce the 'atmospherics' which disturb the radio receiver. Of the various methods adopted for choking off the 'atmospherics', one is to use receiving circuits which respond only to a narrow range of oscillations very different from those produced by a lightning flash.

THE THERMIONIC VALVE

The earlier forms of detector were largely superseded by the thermionic valve, invented by J. A. Fleming, and improved by the inventor himself and other workers in the same field. Fleming was led to his discovery by the fact that increasing deafness rendered it difficult for him to hear signals or messages on the telephone, and he was in search of some instrument which would act as a 'relay', bringing into operation a local current which would enable the messages to be recorded, just as submarine telegraph messages are recorded by the mirror galvanometer and other devices.

In 1883 Edison had observed that a carbon lamp, in which the filament was weak in one place, so that its temperature at that point was higher, did not blacken evenly. There was a strip on the glass fairly free from deposit, and this was in such a position that it appeared as though the particles of carbon were shot off in straight lines, and had been intercepted by the other half of the horseshoe. About the same time Edison was making experiments with lamps of high efficiency. He fixed a metal plate between the limbs of the horseshoe filament, and discovered that when the filament was hot a current flowed between the plate and the positive limb, but not between the plate and the negative limb (Fig. 99). Investigating the Edison effect in 1889, Fleming found that a current would pass freely in one direction only between the plate and the limbs of the filament. The lamp would, therefore, act as a rectifier, and if an alternating current were applied between the plate and the film, the transient currents in one direction would be suppressed. A pulsating current would pass, but always in the same direction.

Fleming explained the phenomena of the Edison lamp as an example of thermionic emission, the escape of electrons from the filament owing to high temperature.

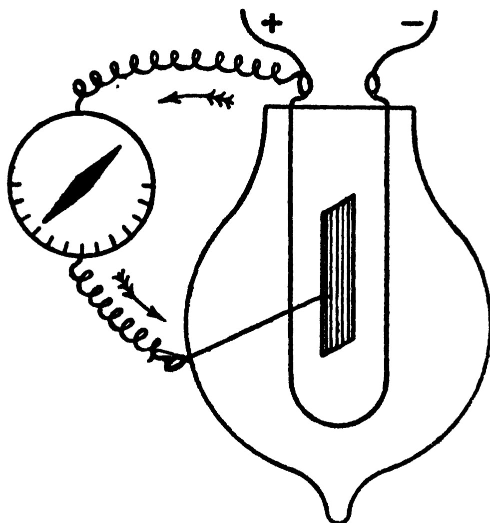


Figure 99. The Edison lamp

It will be remembered that the crystal detector was in essence a rectifier, allowing current to pass only in one direction. Similarly, the thermionic valve will also act as a detector of electric waves. The ways in which it can be used are manifold, but the simplest, which was used by Fleming in 1904, is shown in Fig. 100. Here is shown the aerial, jigger, tuning condenser, valve, battery, and a resistance, the purpose of which is to regulate the temperature of the filament and hence the conductivity of the space between the filament and the plate. The explanation is as follows:

When an electric wave strikes the aerial, there is a surge of electricity backwards and forwards in the coil S and round the circuit of which S forms a part. The upper plate of the condenser is, therefore, electrified alternately positively and negatively. When it is positive, there is at once a flow of electrons or negative ions inside the valve from the filament to the plate which neutralize the positive electricity in the latter; and there is a current through the telephone. As the electricity induced by the wave surges back the top plate becomes negative, there is now no flow of negative ions, and no current passes through the telephone. At each semi-oscillation, there is a gush of electricity, and as the waves follow one another very quickly and at equal intervals the gushes form a musical note in the telephone, provided the gushes occur between the limits of, say, 300 and 1,000 per second. It has been shown by Rayleigh that the ear is most sensitive to interruptions in a telephone circuit when the note emitted corresponds to about 700 vibrations a second.

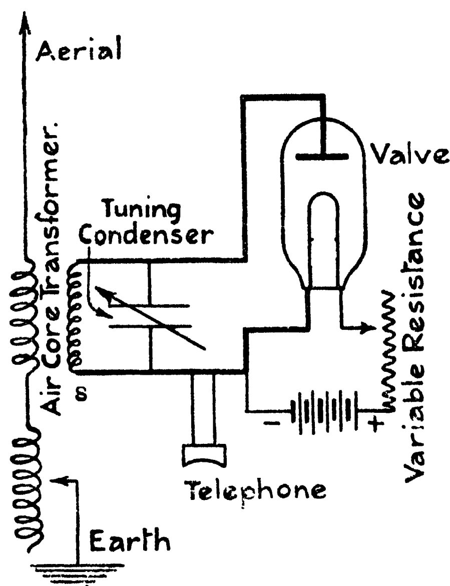


Figure 100. Diagram of valve connections in wireless telegraphy

Though, for the sake of simplicity, the telephone has been shown as part of the main receiving circuit, it is more usual to couple it up than to insert it. Thus, if a coil of wire be inserted in the main circuit, and another coil, the ends of which are joined up to the telephone, is wound over it, any changes in the main circuit will be reproduced in the telephone though there is no direct connection between them. It is this property of the transformer which renders radio apparatus at once so flexible and so complicated; and if the reader cares to examine a series of wiring arrangements of gradually increasing complexity he will find that this complexity is largely due to the separation and coupling of circuits.

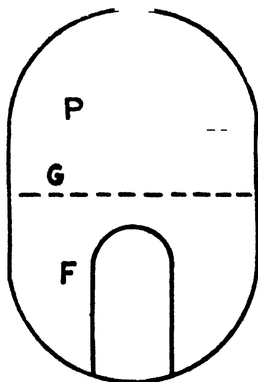


Figure 101. Diagram to illustrate triode valve

Thermionic valves are made in a variety of forms, though they do not differ in principle. Generally, they contain a plate parallel with a filament or a metal cylinder surrounding a straight wire. An improvement was effected by Lee de Forest, who added a third electrode in

the form of a grid—generally a coil of wire—between the plate and the filament (see Figs. 101, 102). The effect of this grid or third electrode, forming what is known as a triode valve, is extremely interesting and not difficult to follow. In the diagrammatic sketch of a triode valve, Fig. 101, F is the hot filament, G is the grid, and P is the plate. The passage of a current is simply a flow of electrons from the hot filament to the plate, and this flow is affected by an electric charge on the grid. If the grid is negative some or all of the electrons travelling towards the plate will be repelled, and the current will be reduced or stopped altogether. But if the grid be positive the current will in general be strengthened.

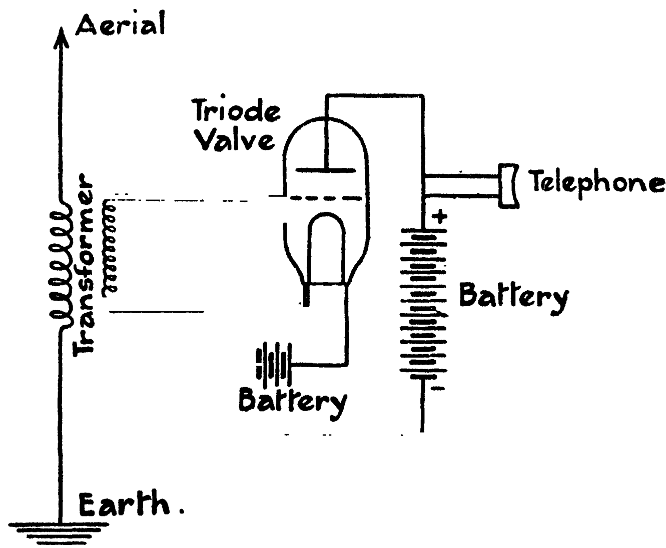


Figure 102. Diagram of connections for triode valve used as detector

Suppose now the triode valve is coupled up as shown in Fig. 102, in which the necessary condensers have, for the sake of simplicity, been omitted. The pulsations of electric waves in the circuit, coupled with the aerial, indicated by heavy lines, will cause rapid alternations in the grid potential, rapid alternations in the flow of electrons from hot filament to grid, and hence rapid alternations in the strength of the current in the telephone circuit. If these alternations occur at the rate of, say, 500 a second, a musical note will be produced.

So far the valve acts as a rectifier, just as the two-electrode valve does. But it has two more remarkable properties which the simpler instrument does not possess. It will amplify the variations which are impressed upon it, and it will act as a generator of oscillations. In the first case,

it will, when the circuits are properly adjusted, amplify either the oscillations which reach it from the aerial or it will magnify the gushes of unidirectional current in the telephone circuit. The first effect is called radio-amplification, and the second audio-amplification. Both effects are due to the fact that owing to the small capacity of the grid circuit a very small amount of energy suffices to change the potential on the grid and to produce a considerable alteration in the current which flows from the filament to the plate. This energy comes from the battery between those two parts of the apparatus. If radio-amplification is required, air-cored transformers are used for coupling, and if audio-amplification is required iron-cored transformers are necessary.

The amplification can be increased by arranging the valves in cascade.

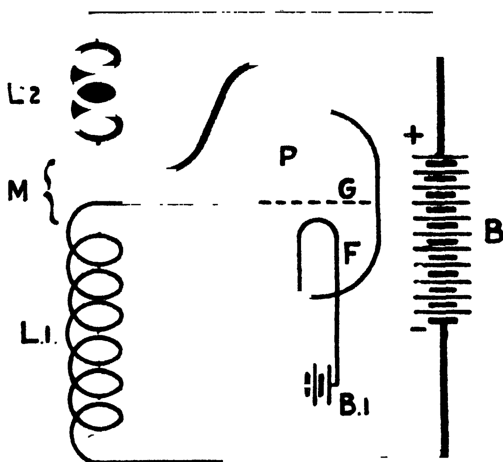


Figure 103. Diagram of connections for triode valve used as oscillator. The coils L_1 and L_2 are coupled

The plate circuit of one valve is coupled to the grid circuit of a second, the plate circuit of a second to the grid circuit of a third, and so on. In this manner the effects can be increased a thousand-fold, and oscillations far too faint to be detected in the older apparatus are now brought well within the range of hearing.

The use of the triode valve as an oscillator will be understood by reference to Fig. 103, from which condensers and resistances have been omitted for the sake of simplicity. Note first the filament circuit, next the plate circuit, in heavy lines, and finally the grid circuit, and keep the two last clearly in mind. Remember also that by means of resistances and condensers these two circuits are tuned so as to have the same

period of vibration. Then starting or increasing the current in the plate circuit will produce by induction between the coils L_1 and L_2 a momentary rush of electricity in the grid circuit *in the opposite direction*. The grid will become negative and repel the negative electrons emitted by the hot filament. Hence the current in the plate circuit will be reduced; the interaction of the coils L_1 and L_2 will cause a rush of electricity making the grid positive; the flow of electrons will be encouraged; and the current in the plate circuit will be increased again. But this increase will immediately result, through the coils L_1 and L_2, in a rush of electricity which renders the grid negative, and the current in the plate circuit again falls. These changes occur over and over again at perfectly regular intervals—an oscillation in the grid circuit and a pulsating but unidirectional current in the plate circuit capable, if the pulsations are not too rapid, of operating a telephone.

Further, if the coil L_1 be coupled with an aerial of the same period, continuous waves will be radiated; while, conversely, if continuous waves of the same period are received by the aerial, pulsations will be set up in the plate circuit. Hence a triode valve is an admirable receiver for continuous waves.

The most important improvement in valves, apart from capacity which will be considered later, is the 'screened grid' or 'shielded' valve. The ordinary triode type would not give a very high amplification over a wide range of wavelength without certain auxiliary devices. The electrode circuits had to be screened as much as possible from one another, and the capacity of the electrodes had to be compensated by the insertion of a condenser, which itself required adjustment for different wavelengths. The number of valves which could usefully be employed in a receiving set was limited by these complications.

The discovery of the generating property of the triode valve was made in 1913. It rapidly came into use in the heterodyne or 'beat' method of transmission. If two musical notes which do not differ greatly in frequency are sounded together, a third sound is produced which has a frequency equal to their difference. Similarly if two electrical oscillations occur in the same circuit there is a reinforcement at intervals which depend upon the difference in the number of vibrations. Thus, let the receiving apparatus be tuned so that it is producing vibrations which are anything from 300 to 1,000 faster or slower per second than those which it is receiving from the aerial. Then reinforcements or beats will occur of a frequency which produces a musical note in the telephone, and this note can be cut up by the dots and dashes of the code. It is possible with this method so to arrange the apparatus that the strays, which were such a nuisance in the early days, are practically eliminated.

One vast improvement which has been made is the degree of exhaustion of the bulbs. The real difficulty is to get rid of the film of air or other

gases which are persistently retained by all solids, and since this can only be accomplished by a high temperature, the bulb is heated during the operation in an electric furnace. The temperature—500° C. to 700° C. —required for the purpose is so high that the bulb might collapse if it were exposed to atmospheric pressure, so the furnace is exhausted by a pump. Most of the air is removed from the globe by a mechnical pump, and the remainder by a special form of pump, of which the Gaede is a good type, or by absorption in charcoal immersed in liquid air. The last traces of oxygen or water vapour are removed by a little magnesium attached to the anode. On heating this is vaporized, the oxygen or water vapour form magnesium oxide, which is a white, non-volatile solid, and the excess of magnesium is deposited as a silver coating on the interior of the bulb. The mirror-like appearance of the valve is, therefore, an accidental circumstance.

The Gaede pump, invented in 1913, is of extraordinary simplicity, having no valves or pistons, and consisting simply of a drum and 'scraper'. Some idea of the principle upon which it works will be obtained from Fig. 104. The drum is grooved and runs in a closed chamber with projections from the casing which nearly touch it. As the drum rotates the air is dragged round with it and a difference of pressure is formed on each side of the projection. This occurs in the first groove, and the compressed air passes into the next groove to be whirled round and still further compressed. Though the difference in a single groove may be small it is cumulative, and, combined with high temperature, a pressure as low as $\frac{1}{100,000,000}$ of a millimetre of mercury can be obtained. When this has been achieved, the conductivity of the valve depends almost entirely upon the production of electrons from the hot filament.

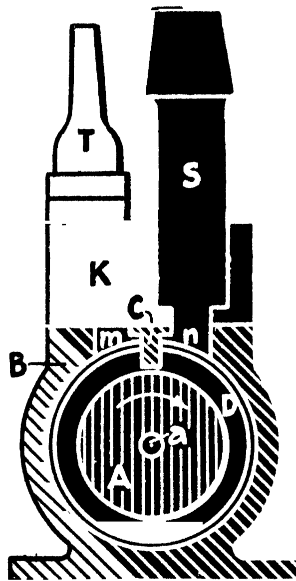


Figure 104. Diagram to explain action of Gaede pump

It will be interesting to examine one important radio invention of enormous value. It was originally impossible for a ship or a shore station to tell from what direction the signals were reaching her; and a number of attempts were made to devise an apparatus which would reveal not merely the signals but also the direction from which they came.

If an aerial consists of two vertical wires, half a wavelength apart,

and connected by a horizontal wire as in Fig. 105 (consider one only) then a wave travelling in the direction of the horizontal wire will induce

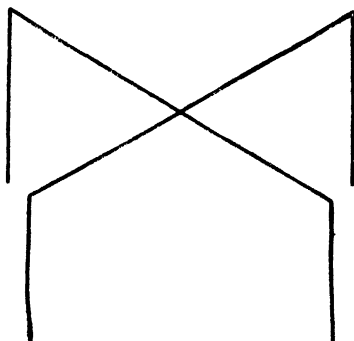


Figure 105. Diagram to illustrate directive aerials

an upward current in one vertical wire and a downward current in the other. A current will flow, therefore, from one vertical to the other,

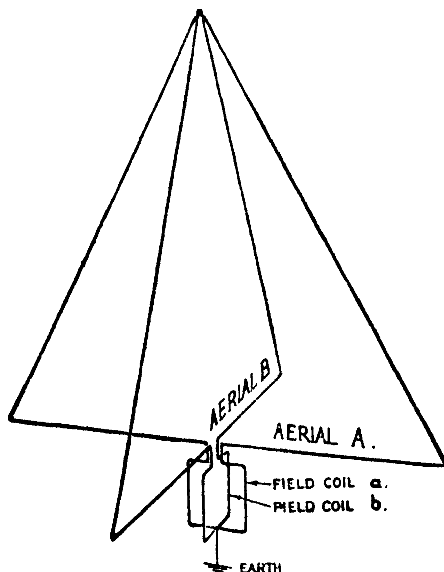


Figure 106. Modern form of directive aerial

along the horizontal wire. A wave reaching the aerials at right angles to their plane will tend to produce an upward or downward current

in both vertical wires. In this case no current will flow through the horizontal wire at all. Should the wave approach from any other direction, a current will flow in the horizontal which will vary in strength with the direction, being greater as the line of approach coincides with the plane of the aerial. In 1907 Bellini and Tosi patented the application of two of these aerials placed at right angles to each other, so that the waves would produce their maximum effect in one when they produced

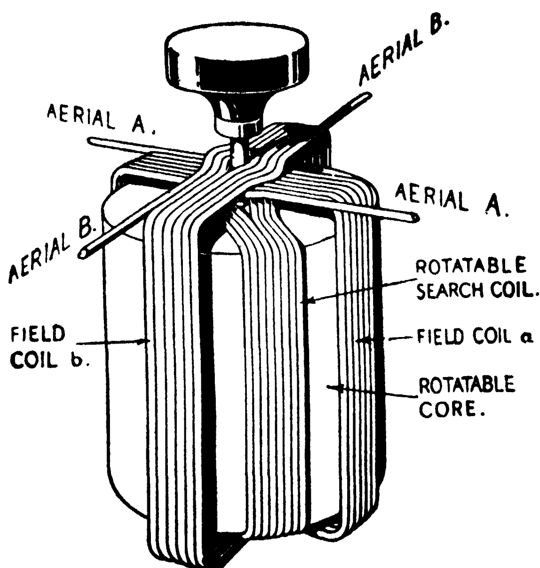


Figure 107. Diagram to explain the radio-goniometer or direction finder

no effect in the other. An important part in the invention was the radio-goniometer, by means of which the effect in two aerials was compared. This consisted of two coils, one in circuit with each aerial and mounted at right angles to one another, as in Fig. 106. A third coil, called a search coil, connected with the receiving apparatus, was mounted inside the others, so that it could be rotated into a position parallel with either of them. The direction of the plane of this coil when the loudest signals were received indicated the direction but not the sense of the incoming waves.

RADIO BROADCASTING

Sound consists of vibrations which are propagated through the air by wave motion. The sounds of speech are of two kinds—vowels and

consonants. For every vowel there is a definite kind of wave, but it is not a wave produced by a simple vibration. The pitch of the note is due primarily to the vibration set up when air is expelled from the lungs through the vocal cords, but it is profoundly modified by the mouth, and the fundamental sound is accompanied by harmonics. A simple explanation will make this clear. The note emitted by a plucked violin string depends upon its length. If the length is halved the number of vibrations per second (i.e. the pitch) is doubled. If only a third is taken, the pitch is three times as high. The string may vibrate as a whole and in parts at the same time. The note given by the whole string is called the fundamental; those given by the parts are called harmonics. The vowel sounds contain both. The consonantal sounds are never continuous. They modify the beginning or end of those which represent vowels.

The telephone transmitter consists of a thin metal disc or diaphragm with granules of carbon packed loosely behind it. A current of electricity passes through these, and when a person speaks into the mouthpiece the disc vibrates, the resistance offered by the granules alters, and variations in the strength of the current are produced which flow along the line to the receiver. The receiver consists of an electro-magnet round which the line current flows. One end of the magnet lies just behind a metal disc, and variations in the line current cause the disc to vibrate, producing sounds more or less similar to those which gave rise to the current variations.

In radio the waves must be caused to wax and wane with the waves of sound corresponding to human speech. Trains of wave which themselves vary in strength will not serve the purpose. They must be *continuous*, and produced by apparatus so sensitive that variations in the current in a telephone circuit can be impressed upon them; and they must be received by an apparatus so sensitive that it immediately responds to these variations. An apparatus suitable for these purposes is found in a three-electrode valve, used as an oscillator at the transmission end, and a series of similar valves used (*a*) to amplify and (*b*) to rectify the waves at the receiving end.

One of the chief disadvantages of radio telephony is the fact that you cannot 'cut in' when a man is speaking to you. Before 'listening' can become 'speaking' a switch must be thrown over.

The development of radio enormously increased the utility of radio-communication for publicity, entertainment, and education. While few people could interpret the dots and dashes of the Morse code, millions could purchase a receiving set and listen to words and music poured into the ether from transmitting stations all over the world. In 1922 the British Broadcasting Company was formed.

The instrument makers, and especially the valve makers, were quick to see the possibilities. The programme of a distant or foreign station

required amplification in order to render it audible. Condensers, transformers, high-tension batteries and accumulators, and valves were improved in design and construction and, owing to the demand, produced more cheaply. And though each receiving set would supply several headphones, these were rather expensive, and, to many people, uncomfortable. So the loud-speaker was perfected, and the instruments resounded more strongly to certain notes. It would carry us too far to describe how these disadvantages have been overcome. The reader will be aware, however, that these instruments can be made to give a sufficient volume of sound to fill a small room without unpleasantness, and also to enable 20,000 people to hear a speech in the open air. The microphone used in small loud-speakers requires very little power to work it, but the volume of sound is correspondingly small. The horn acts as an amplifier. In some instruments a large volume of air is set in motion by a pleated paper disc, which is operated by the diaphragm, and this type is replacing the horn type gradually.

BEAM RADIO

Beam transmission depends primarily upon the fact that when two or more aerial wires are set in line the electro-magnetic radiation is almost entirely at right angles to the plane of the wires. A series of such wires, in one plane, will radiate from both faces. If the plane is east to west, the radiation will be northwards and southwards. If the plane is north to south, the radiation will be eastwards and westwards. The longer this plane or 'sheet' of wires and the more wires there are per unit of length in the sheet the more complete is the radiation at right angles to it. The length of the plane or sheet horizontally is always several wavelengths.

As the plane or sheet will radiate in two directions, a reflector is required. This is supplied by a similar sheet of wires, but more closely spaced, and suspended one-quarter or three-quarters of a wavelength behind the transmitting aerials. Such an aerial will radiate a beam which only diverges about 10°, and the beam is received by an aerial of precisely similar construction.

TELEGRAPHED PHOTOS

The transmission of pictures by telegraphy is not exactly new, but it is only recently that the principal daily papers have adopted it as a more or less regular practice. It is carried out with the aid of the photo-electric cell.

When Hertz was making his experiments in 1887 with electric waves, he noticed that a spark passed more readily across a gap when it was

illuminated. Subsequently, it was discovered that certain bodies, such as sodium, potassium, rubidium, etc., emit electrons (see Chapter XX) rather freely when exposed to light, and these electrons, which are particles of negative electricity, constitute, when in motion, an electric current. A photo-electric cell consists of a vacuum tube coated on the inside with one of these light-sensitive metals. The current which passes through it varies with the strength of the light which falls upon the metal (sodium, potassium, or rubidium), and as the photograph is 'explored' the light and shade signals are delivered to the line. At the other end this varying current operates a string galvanometer. This consists of a fine wire suspended between the poles of a powerful magnet. The fine wire carries the weak but varying current, and with each variation it moves in the strong magnetic field. In its steady position it closes an opening through which light would pass. With each movement it allows light to fall on a piece of sensitized paper, wound on a cylinder, and moving exactly in the same way as the original photograph moves at the transmitting end.

The photograph may be analysed by dots, a spot of intermittent light being flashed up and down or across the picture, and a mirror galvanometer may be used to communicate the light and shade to the sensitized paper; but the principle is the same.

TELEVISION

Television presents a more difficult set of problems. It does not involve photography. An image of a distant person or object is to be projected upon a screen. The person or object has to be analysed by a line or spot of light in the same way that the photograph is analysed in photo-telegraphy. That is not a difficult task. But in producing the image the last line or spot must be recorded before the first has faded from view. In Chapter XIX it is explained that as an image falling upon the retina—the sensitive screen at the back of the eye—persists for only one-tenth of a second, the pictures on the cinematograph screen must follow one another at a rate of not less than ten a second in order that a continuous impression may be formed. Similarly in television, the whole of the picture must be traced in lines or in spots in less than that interval if the reproduction is to be seen as a whole.

Let us examine the general arrangement. Firstly the object must be brightly illuminated. Secondly there must be a photo-electric cell. Thirdly the light from each small area successively of the object must fall upon this cell. Baird used three discs, one with a series of radial slots round the edge, one with a spiral slot, and the third with a series of lenses arranged in a spiral. The radial slots rendered the light from the picture intermittent, the spiral slot determined the portion of the object

from which the light is reflected, and the lenses focused this light upon the photo-electric cell, see Plate LV*a*. The varying current from the transmitter operated a Moore lamp in which the vacuum tube was a spiral inside a globe, see Plate LV*b*, at the receiving end. The gas in the tube was neon, which gives a brilliant orange-red glow. The light from

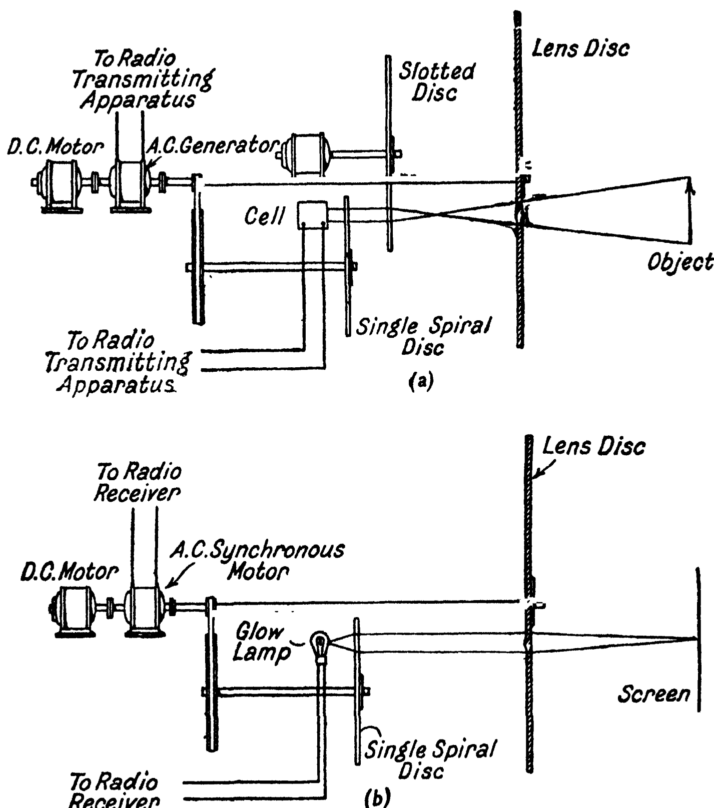


Figure 108. Diagram of Baird's (*a*) transmitting arrangement, (*b*) receiving arrangement

this lamp passed through a system of discs and lenses, similar to those at the transmitting end, and fell upon a screen.

Radio television was achieved by coupling a radio transmitting set at one end of this apparatus, and a radio receiving set at the other. The success which has been achieved is a very wonderful development of the physical investigations of the last fifty years, and it represents the work of many men in many places at many times.

THE GROWTH OF TELEVISION

Britain was the first country in the world to have a regular public Television Service and with the exception of the war years has enjoyed this ever since 1936.

Television has rapidly developed into a leading form of home entertainment in all those countries fortunate enough to have a television service. Great public occasions, major sporting events, variety, newsreels, are all brought to viewers' homes by this invention.

The foundations of the electronic television system were laid by the British scientist Campbell Swinton, who in 1908 outlined a scheme for obtaining 'distant electric vision' by electronic means. When we consider that the devices he suggested as necessary to implement this idea—cathode-ray tubes—were as then unrealizable, we appreciate how tentative and futuristic his plans must have sounded to his contemporaries.

However, within less than thirty years, scientists transformed Campbell Swinton's imaginative theories into a practical workable system of electronic television.

For many years television development went ahead on quite different lines to the all-electronic system propounded by Campbell Swinton. Much work on the mechanical system was pioneered in this country by J. Logie Baird, who gave a demonstration of his system as early as January 1926.

The limitations of mechanical systems were soon realized and about 1930 a team of research scientists mobilized by the late Alfred Clark were set to work at Electrical and Musical Industries Ltd., at Hayes, to fulfil the far-sighted prophecies of Campbell Swinton.

These men, distinguished by their oustanding work in the fields concerned, started investigations under the direction of I. Shoenberg, then Head of E.M.I. Research. We are indebted to E.M.I. Sales & Services Ltd. for the above and following information.

The ever-growing increase in the number of television viewers is a tribute to this fundamental research which was undertaken at not inconsiderable financial risk and culminated in the television system which has been used by the British Broadcasting Corporation since 1936.

The realization in practice of Campbell Swinton's ideas was made possible by the development of the 'Emitron' camera pick-up tube and 'Emiscope' cathode-ray tubes. The camera tubes convert the light and shade of a televised scene into corresponding electrical impulses and the Emiscope tube enables the television receiver to build up the picture from the electric signals it receives.

In 1934, E.M.I. were asked by the Television Committee set up by the Postmaster General of Great Britain to demonstrate their revolutionary Electronic Television System.

The demonstration was remarkably successful and so clearly superior to any other television system that it was subsequently adopted by the British Broadcasting Corporation as the standard television transmission system for Great Britain. Construction of the London Television Station at Alexandra Palace was commenced, and in 1936 regular daily transmissions were started, using this system now known as the Emitron Television System. This was the first regular public television service in the world. The television equipment for the London Television Station was designed and manufactured in the E.M.I. Laboratories and much of it is still in use today.

The vision transmitting equipment for the B.B.C. Television Stations at Sutton Coldfield, Kirk o' Shotts, and Wenvoe was also designed and supplied by E.M.I. The last two are the most powerful television transmitters in the world and have an output of 50 kW.

These stations, together with the other high-power television transmitter recently opened in the North of England will serve over 80 per cent of the population of Britain. Five low-power stations bringing the population coverage up to 90 per cent are envisaged as part of the B.B.C.'s total plan.

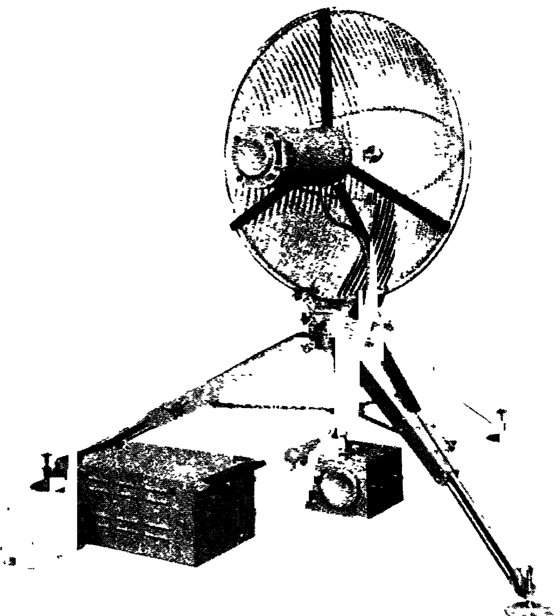
The transmitter at the Kirk o' Shotts television station in Scotland is capable of delivering a peak power of 75 kW. into the aerial. This is done by means of a technique called low-level modulation.

The transmitter gives a third more power than that at Sutton Coldfield, though it is only a little more than half the size. The power is conducted to the aerial by means of a 'locked coil rope' feeder. This is designed on the pattern of a coal mine lift rope. These are specially constructed so that they remain exactly vertical when suspended. By adopting this method of construction for the copper electrical conductor, the efficiency of the feeder in conducting the power from the transmitter to the aerial is increased.

There is a complete absence of electrical reflections in the feeder, which leads to the production of clearer and more sharply defined pictures.

As pioneers of television, it is perhaps natural that E.M.I. should have been responsible for many of the major advances in television technique that have taken place since 1936. Perhaps the most striking of these was the development of the C.P.S. Emitron type of television camera. C.P.S. stands for Cathode Potential Stabilization and is a method by which the results obtained enable transmissions to be made under lightning conditions previously regarded as impossible. The greatly increased sensitivity and freedom from unwanted shading effects of the C.P.S. Emitron Camera allow perfect outdoor transmissions even under the worst possible conditions.

Often when the commentator on the spot is complaining of failing light the television viewers are enjoying perfect viewing. C.P.S. Emitron



(*E M I*)

LV*a*. A micro-wave link for reflecting very short television waves, enabling a picture to be picked up and transmitted



(*E M I*)

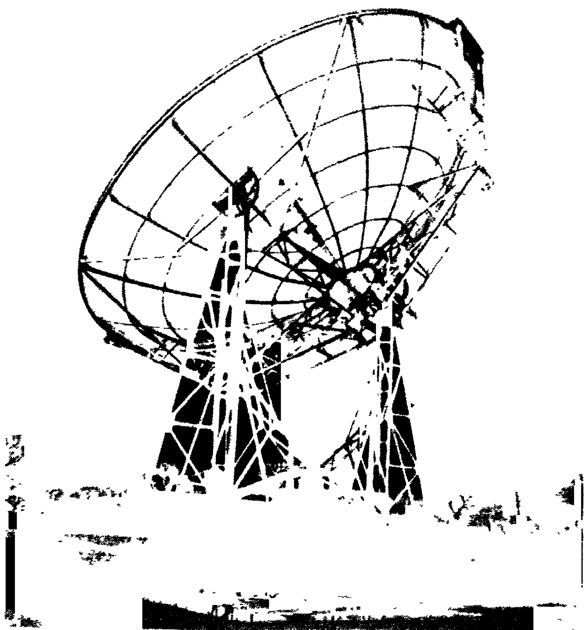
LV*b*. A six-lens television camera



LVI*a*. The same subject photographed on an ordinary plate



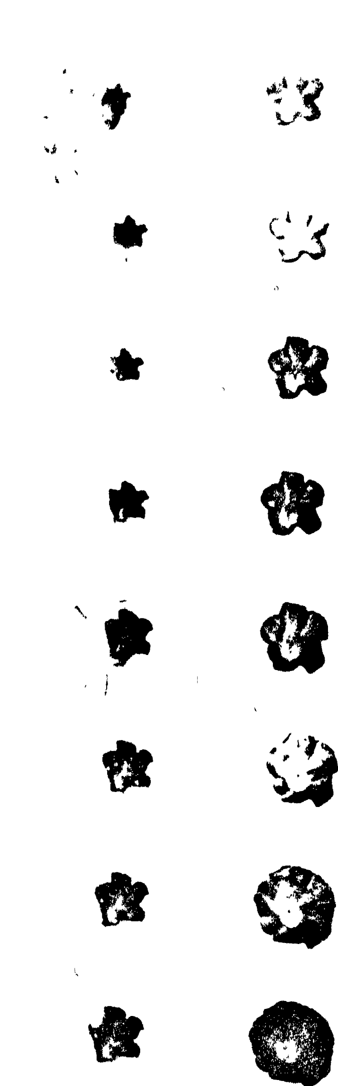
LVI*b*. and a panchromatic plate



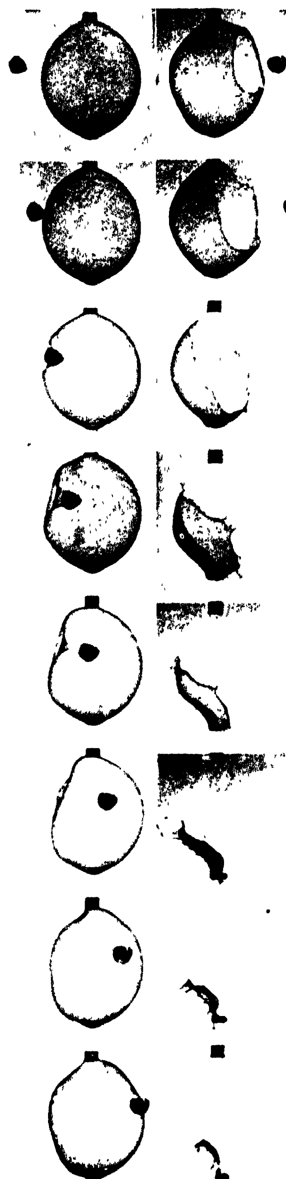
LVIIa. A 30-ft. steerable radio telescope at Jodrell Bank



LVIIb. Lake Como plotted by radar. The mountains cast shadows which, like the lake, appear black



LVIII*a*. Slow motion and fast: (*a*) opening of a convolvulus flower



LVIII*b*. (*b*) breaking a soap bubble with a bullet

cameras were largely responsible for the success of the televising of the 1948 Olympic Games at Wembley.

From the Emitron Laboratories has also emerged a new type of 'Flying-Spot' Television Film Channel which makes possible the televising of films. Equipment of this type is today ensuring that films that are televised give the same high quality pictures as studio broadcasts.

In 1949 an important event occurred in the field of operative surgery. A specially developed C.P.S. Emitron Camera and ancillary equipment were installed in the operating theatre of Guy's Hospital, London, to enable operations to be televised and simultaneously viewed by students and doctors on remote receivers. This was the first permanent type of installation of its kind and has been described as 'a revolutionary advance in the teaching of operative surgery'.

The Festival of Britain provided a striking opportunity for showing the great achievements of television. The latest television equipment designed by E.M.I. was exhibited at the South Bank Exhibition. This equipment included a remarkable new 6-lens C.P.S. Emitron Camera and portable C.P.S. Camera Channel.

The new camera has many outstanding features and is designed to fulfil completely the most exacting requirements of producers and operators.

Another development of especial significance is the Emitron microwave relay link. Two of these were used by the B.B.C. in the recent Franco-British television programmes. Using a new klystron valve, developed in the E.M.I. Research Laboratories, they are able to operate successfully at distances hitherto impossible at the very high frequencies at which the links function.

TELEVISION LINKS

The distance at which televised pictures can be clearly received is limited, because very short waves proceed in fairly straight lines, and hence are cut off by the curvature of the earth. This limitation is overcome by focussing the waves so that they can be picked up by a distant station, and re-transmitted. Up to 1952, the longest 'jump' of this kind was accomplished by bringing the Paris television programmes to England through a series of 'television links'. The largest of these was over the 49 miles from Swingate to Wrotham. Another big 'hop' was over 40 miles across the English Channel, from Alembon to Swingate.

The principle of the links is simple. It consists of a mirror which will focus the very short micro-waves, which can then be picked up at the receiving end by a similar reflector (Plate LV*a*).

When it is desired to make a television outside broadcast (O.B.) transmission, modern practice in Britain in 1952 is to have a very high

frequency (V.H.F.) link connection between the O.B. site and Alexandra Palace (or Sutton Coldfield).

In the past it has not been possible to obtain very great ranges with such V.H.F. links due to several factors, an important one of which was the lack of suitable valves to produce the power required at the very high frequencies involved.

Incorporated in two Emitron Microwave Links now being delivered to the B.B.C., however, are new type klystron valves which enable these link transmitters to operate on powers of the order of 3–5 watts. It is thought to be the first time that such powers have been utilized on links of this type. The development of the special valve involved over three years of extensive research.

The success of this work is shown by the fact that under not very good conditions, successful working of these links at full operational reliability has been obtained at distances of well over 45 miles.

Another feature of these links—which operate on a wavelength just less than 3 in.—is that frequency modulation is used on each of the three channels provided.

These three channels are vision, programme-sound and talk-back. The last named facility, believed to be supplied on such links for the first time, enables the O.B. producer to keep in touch with, or receive instructions from transmitter control.

These units may be loosely thought of as Television Searchlights and the action of the parabolic reflector (about 4 feet in diameter) which is of slatted or lath-like construction acts similarly upon the V.H.F. radio-waves as does the reflector of an ordinary searchlight.

These Emitron links have an aerial power gain of 1,000. Having such power available it is possible to design the aerial reflector in such a way as to give a fairly wide beam angle which makes setting-up a much easier task.

The slatted construction of the parabolic reflector aerial offers less wind resistance and the decrease in weight makes them more transportable.

A SIX-LENS TELEVISION CAMERA

At the Festival of Britain the E.M.I. Company demonstrated their 6-lens C.P.S. Emitron camera, working on 625-line definition. The six lenses are carried in a turret, so that any one of the lenses can be used for viewing. This provides a very wide and flexible range of viewing angles (Plate LV*b*).

The lenses not in use are below the level of the camera top, and consequently do not obstruct the operator's view. The operator is assisted by an electronic view-finder which throws the view in a white screen aluminized Emiscope viewing tube.

The pick-up tube contains a C.P.S. Emitron of greatly increased sensitivity. The tube has a linear characteristic and a colour response almost identical with that of the human eye. It sees, so to speak, very much what the human eye sees.

RADAR

The location of the origin of radio signals for the determination of the places of ships at sea was one of the earliest radio developments. This method of locating the places of ships depended, of course, on the ship's radio transmitters sending out radio waves. It was of great value both for bringing aid to distressed ships and to the locating of military enemy ships. The reply to the detection of one's location by an enemy was radio silence. If a ship did not send out radio waves, its position could not be located by radio direction-finding.

The need for some method of locating hostile vessels without depending on the emission of radio waves by them was enormously increased in urgency by the threat of war in the 1930's. Britain especially was particularly defenceless against surprise air attack. Such was the degree of urgency that any suggestion was given consideration. Many members of the public suggested that some kind of death-ray was needed in order to put hostile aircraft out of action. It was from the serious consideration of this suggestion that British radar developed. R. A. Watson-Watt, to whom the problem was referred for advice, reported that while the invention of a death-dealing ray for destroying a hostile aircraft seemed to be beyond the range of contemporary physics, its location was not. A radio-beam sufficiently intense to shrivel up an aircraft would require more energy than any known process would concentrate in a radio-beam, but the energy in a radio-beam reflected from an aircraft was sufficient to be detected by known physical processes. In short, a death-beam was impossible on the basis of existing physical knowledge, whereas the location of an aircraft by the reflection of radio was theoretically possible. On the basis of Watson-Watt's report, a determined effort was begun to see whether location by radio-reflection was experimentally possible. The word 'Radar' is an abbreviation for the finding of Radio Direction and Range. Its spelling, either forwards or backwards, gives the same word, and neatly suggests the idea of an echo.

It had been shown in 1924 by E. V. Appleton that the height of the 'Heaviside Layer' could be measured by the time taken for a radio wave (which travels at 186,000 miles a second, the speed of light) to rise up to it, be reflected, and return to the earth's surface. He found that the layer was at a height of 60 miles. Thus Appleton had shown that the distance of a surface could be determined by radio reflection.

As a reflecting surface surrounding the earth, the total area of the Heaviside layer is even greater than that of the surface of the earth itself. The location of a point or a patch in, for practical purposes, a surface of almost unbounded extent, is a problem with quite new features. It does not necessarily follow that because a vast spherical radio mirror like the Heaviside layer will reflect radio-beams, so that the reflections can be detected, then an aircraft, which is virtually a point in the atmosphere, will also reflect with sufficient strength radio-beams, so that their reflections can be detected. In 1935, Watson-Watt took a van with radio receivers to a place about ten miles from the powerful short-wave radio station at Daventry. An aircraft was directed to fly over the station while the short waves were being transmitted. It was found that faint reflections of these waves from the metal surface of the aircraft could be detected by the receivers in the van. Subsequently, it was appreciated that such interferences had been observed involuntarily in the past. In 1931, for example, the British Post Office engineers had noticed that some of their short-wave radio receivers were disturbed when an aircraft passed within four miles of them.

A laboratory was established at Orfordness on the Suffolk coast, to work on the host of problems which had to be solved in order to convert these experimental hints into an effective system of radio-location, or radar. Watson-Watt and his team set about designing a special transmitter to send out the best and strongest kind of beam for reflection, and to design receiving apparatus which would record the returning reflection visually on a fluorescent cathode-ray tube. In June 1935, an aircraft could be followed by the movement of a spot on a cathode-ray screen up to a distance of forty miles, and in July one spot was seen on a screen to split up into two, showing that a formation of aircraft had split into two parts.

By September, the height of an aircraft flying at 7,000 ft. at a distance of fifteen miles was successfully measured. By January 1936, the bearings of an aircraft at a distance of twenty-five miles were determined successfully. In the spring of 1936 the range was raised to seventy-five miles. A systematic watch was kept on the air-liners between London and the Continent, which passed near the station. In 1937 the construction of a chain of twenty watching stations, from the Solent to the Firth of Tay, was begun.

The five stations on the Thames Estuary watched Neville Chamberlain's plane as it flew to Munich in September 1938. Already, two million pounds had been spent on this secret weapon.

Even before this, the training of the Royal Air Force fighter pilots in the new tactics of air-fighting arising from the use of radar had begun. Consequently, when the Luftwaffe made its onslaught on London in 1940, the radar warning system was sufficiently developed to give the

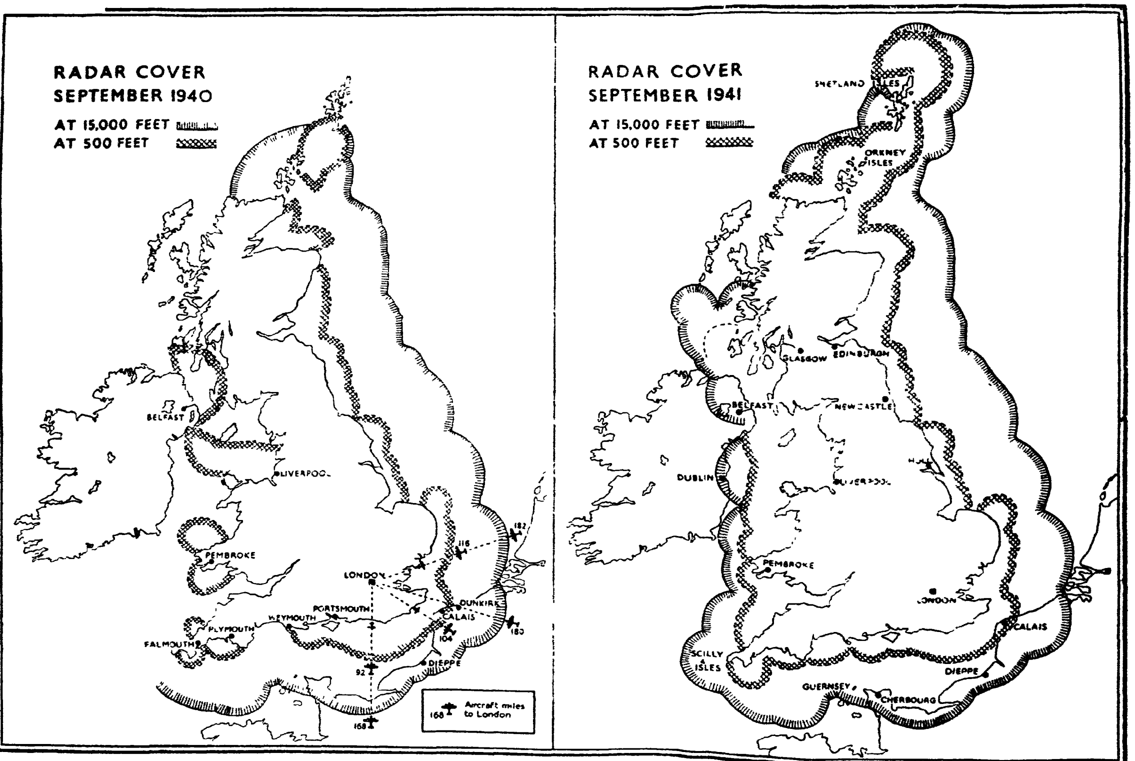


Figure 109. Radar cover of Great Britain

fighters warning, and the pilots were already fully trained in the new tactics of aerial combat between fighters and bombers. The Luftwaffe was not aware of the degree of the development of radar, and was not experienced in the new aerial combat tactics. One of the reasons why the aerial attack on London suddenly ceased was that a considerable period of training in new tactics would be necessary if the raids were to continue without disastrous losses.

In order to obtain sharply defined echoes, which will correspond distinctly with each separate reflecting aircraft or object, the radar transmits not a continuous wave, but a series of very short sharp pulses of waves. Each pulse is made to mark the time of its emission, and the time of return of its reflection on a screen. The distance between the two spots, known as 'blips', on the screen corresponds to the distance of the aircraft. If two aircraft one-tenth of a mile apart on the line of observation are to register separate spots on the screen, the pulse must be less than one-millionth of a second in duration. This is comparable with the duration of a lightning-flash.

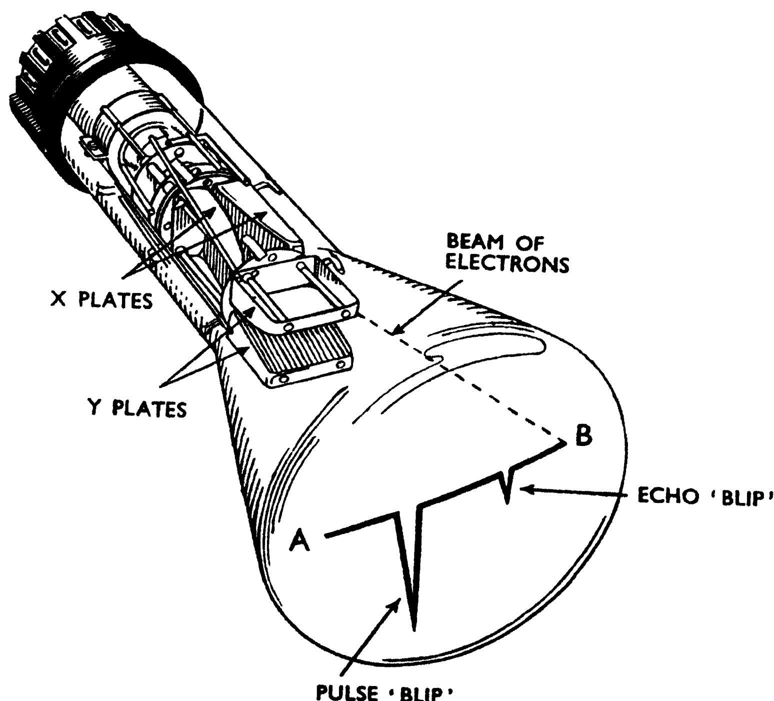


Figure 110. The Cathode-ray tube

The cathode-ray tube used in radar has two sets of plates—the X and the Y plates—set at right angles, by which electrical forces can be exerted on the beam of electrons shot from the cathode on to the end of the tube, which is covered with a fluorescent substance. An apparatus sends a current to the X plates which causes the fluorescent spot to move at a constant and known speed from A to B. During the passage of the spot, the same apparatus operates the pulse transmitter. The pulse immediately reaches the receiving aerial, which is connected to the Y plates. These consequently exert a force on the cathode-ray beam, which pushes it momentarily off its track, and the spot makes a zigzag, registering the pulse blip. The pulse meanwhile flies outward, reaches the aircraft and is reflected back. It produces a current in the receiving aerial and Y plates, which causes a second zigzag, giving the echo blip. The distance of the aircraft is given by the distance between the two blips, and can be read off at once from a scale on the screen, without calculation.

The precision of information given by radar depends on the wavelength used. The shorter the wavelength, the more exact the information.

Further, it is much easier to focus short waves, for the shorter the wave, the smaller, and hence less expensive and more manageable, the mirror required.

One of the basic problems in radar has therefore been the development of powerful sources of very short waves. The most remarkable of these is the cavity magnetron. This is a form of radio valve in which the electrons emitted by the cathode are submitted to a magnetic as well as an electric field. As the electrons are carried round in the magnetic field they sweep by a series of oscillatory circuits and maintain oscillations in them, which are sources of very short radio waves.

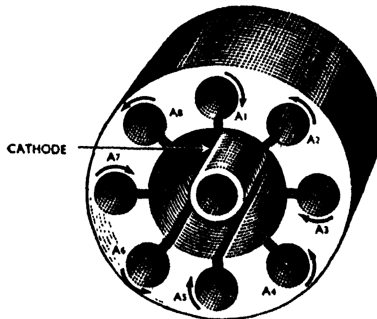


Figure 111. Diagram of the cavity magnetron

The cavity magnetron is shown diagrammatically in Fig. 111. It may be no bigger than a watch.

Though small and delicate, magnetrons give pulses of hundreds of kilowatts of energy for a millionth of a second, without destroying them, just as it is possible to get brilliant flashes from an electric lamp if subjected to an over-voltage for a very short time.

The first short-wave radar set regularly used as a weapon was the 271, designed by the Admiralty Signal Establishment. It operated on ten-centimetre waves. Its beam was focused by a cheese-shaped reflector, which gave a narrow beam in the vertical plane, suited to the detection of submarine conning towers and periscopes. It was of great value in the campaign against the U-boat.

The provision of good radar warning sets made it possible to run fast liners, like the *Queen Elizabeth* and the *Queen Mary* without the protection of warships.

The increase in precision due to short-wave radar enabled anti-aircraft gunnery to be far more accurate and effective. But the most brilliant innovation was made with the proximity or self-acting radio fuse. This was proposed by W. S. Butement. It consisted of a tiny radio transmitter and receiver fitted into a shell. When the shell is fired, the transmitter begins to emit radio waves. As the shell approaches its target, the radio waves which have shot on in front with the speed of light, reach the target and are reflected back. They are picked up by the receiver in the shell. It is arranged that when the period between the emission of the waves from the shell and their return is below a certain small value, indicating that shell and target are close together, the shell explodes. It is very remarkable that the radio apparatus in the shell is robust enough to stand the propelling explosion, and is subsequently precise enough to work accurately to millionths of a second. The production of proximity fuses in quantity which would work reliably was solved by American scientists and engineers. It was American proximity fuses which were used in shooting down the flying bombs used to attack London.

During the first two years of the Second World War, bombing was very inaccurate, and it became evident that it was wasteful of life and resources. Radar technique was applied in various ways to locate targets on the ground, such as towns and factories, more precisely.

How could a target be found, in spite of darkness, cloud or fog? One method, known as Gee, consisted of guiding the bomber by radar pulses sent out from pairs of radar transmitters. The pulses produce blips on the cathode-ray tube in the bomber, and the distance between the blips will be proportional to the difference of the distances between the aircraft and the two stations.

Suppose that H_1 is on a course which passes over the target, and in which PA–PB is always constant, then the point on the course exactly over the target can be given when the aircraft reaches a track known to

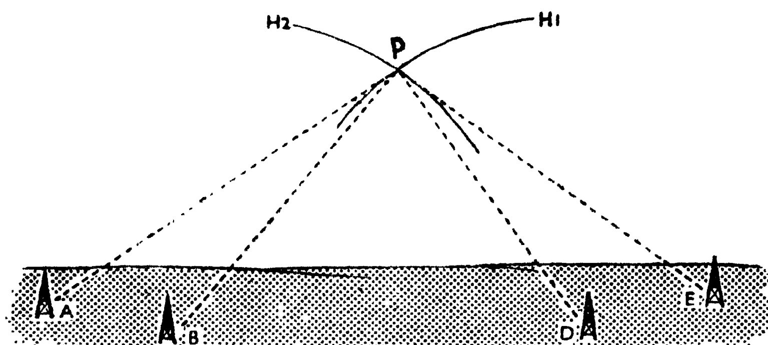


Figure 112. The principle of 'Gee'

pass over the target, in which PE–PD is constant. Curves of this kind are hyperbolas. Thus if a pilot wishes to arrive exactly over a target, he chooses a hyperbolic track which passes over the target on his chart, and flies along this by keeping PA–PB constant, which he does through watching the blips from A and B on his screen, and keeping them at the proper distance apart. He picks out the exact spot on H_1 by observing when he crosses track H_2. He knows this by observing a second pair of blips due to stations D and E. When these are a certain distance apart he will know he is on track H_2. Thus at the right moment when the two tracks cross, he will drop the bombs and know he is exactly over the target. This was the system used to destroy and disorganize the great armaments factories in the Ruhr.

Another system, called Oboe, guides the aircraft along the circumference of a great circle which passes over the target. If the aircraft strays to the right the pilot hears a series of dashes in his earphones. If it strays to the left, he hears a series of dots. As long as it keeps accurately on its course, he hears a high-pitched continuous buzz. The station that sends out the guiding pulses, and worries the aircraft this way and that is called the 'Cat'. Another station, which warns the pilot when he is over the target, and should drop his bombs, is known as the 'Mouse', because, as it were, it causes the bombs to dart down the appropriate hole. The release of the bombs could be made independent of the pilot, who would be left free to look after his controls.

The Oboe system enabled bombs to be dropped from a height of 30,000 ft. at a distance of 150 miles so that on the average half of them fell within 150 yards of the target.

These radar methods have transformed the arts of navigation and mapping. The old methods of navigation by sun and stars gave the place of a ship at sea to within about one mile, and an aircraft to about eight miles. But radar and aerial photography will give places to an accuracy

of a few yards with great speed. They have enabled the earth to be surveyed with a new order of accuracy, which will lead to much more exact knowledge of vast areas hitherto not easily accessible, and small variations which could not hitherto be detected, and which will reveal unsuspected properties and processes in the earth. In 1952, a squadron of Lancaster aircraft completed a six years' survey of Africa. Over one million square miles was mapped, especially in order to reveal new possibilities of harbours, hydro-electric plants and mines.

The most romantic of the war-time radar inventions was the development of radar television, known as H_2S. This consisted of scanning the target, perhaps a town or factory, with a narrow beam of very short radio waves. These were reflected back and recorded on a cathode-ray screen in the pilot's cockpit. The nature of the reflection depended on the nature of the target, whether it consisted of soil, stone or water. Hence the reflection of the scanning beam revealed the differences in character of different parts of the target, and hence revealed their outlines. For instance, the shape of a city beside a lake, such as Berlin or Hamburg, was clearly revealed. As the short-wave beam penetrated fog, cloud and smoke, the city outlines were shown up, in spite of the presence of such obstacles, due either to climatic conditions or to protective action.

A mature form of this apparatus produced a beam of waves like a fan, which was very narrow in the horizontal plane, and very broad in the vertical plane. The aerial rotated once a second, so that the beam

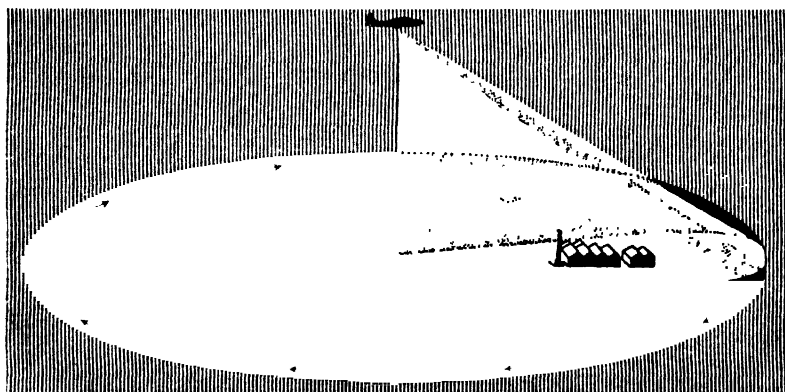


Figure 113. Diagram of a rotating beam of H_2S

swept over the target on the ground. The reflections were recorded on a cathode-ray screen along an illuminated radius that rotated at the same rate as the beam. They built up an outline of the features of the target, which glowed on the screen for a short time (Plate LVII*a*).

This apparatus was used in the very destructive raids on Hamburg, Berlin and Leipzig. But its most important military effect was in the war against U-boats. These had successfully evaded attacks by picking up the radio waves from hostile aircraft, and submerging into safety. The introduction of H_2S enabled the U-boats to be located in the dark, and the beams from H_2S were very much more difficult to detect. As a result of the introduction of H_2S, the sinking of ships by U-boats fell from 700,000 tons in March 1943 to 100,000 in August 1943, and did not increase again.

The development of H_2S was due especially to A. C. B. Lovell. Since the War, he has applied his radar technique to physical research and has become one of the chief founders of a new branch of science—radio astronomy.

RADIO ASTRONOMY

At the end of 1931, the American physicist Karl Jansky was studying the direction of arrival of atmospherics from thunderstorms. He was using a big aerial about fifty feet wide, tuned to receive fifteen-metre waves. The aerial was designed to be directional in a horizontal plane, and could be wheeled round on a brick runway, so that the direction from which atmospherics came could be determined. He noticed that even when there were no thunderstorms, the arrival of radio waves was sometimes registered by a hiss like the background noise in an ordinary receiver. He tried to find the direction from which they came by revolving his aerial, and concluded that they came from the plane of the Milky Way. He found that the peculiar hiss rose to a maximum intensity very nearly, but not quite, once every twenty-four hours. In fact the interval was twenty-three hours fifty-six minutes. This is the period of the earth's rotation relative to the stars, which is not quite the same as the twenty-four hour period relative to the sun. This observation was far in advance of its time, and its significance was not fully understood for fifteen years.

Jansky's observation was confirmed by an American radio amateur Grote Reber, who suggested that these waves coming from outer space were generated by some atomic process in the very rarefied interstellar gas.

In 1935 Skellet, and in 1939 Appleton, had noticed reflections of radio waves from the ionosphere, which appeared to be due not to the ionosphere itself, but to meteors. When particles of dust which constitute meteors rush through the air they are raised to a very high temperature by friction, and vaporized. The heat causes the air and the vaporized atoms to be ionized or electrified. Hence the meteor trails form stretches of ionized gas, and this is able to reflect radio waves, and hence give

radar echoes, just as the Heaviside layer itself is able to reflect radio waves.

In 1945 J. S. Hey and others had been using radar operating on a four-metre wavelength for detecting V2 rockets. They had noticed that some of the observed echoes came not from rockets, but from meteors, and he showed how the direction, or radiant, from which the meteor came, could be determined.

After the Second World War, a large quantity of the new highly-developed radar apparatus and technique became available for ordinary scientific research. Hey, Lovell and others swiftly extended the lone pioneer observations.

Lovell constructed at the Jodrell Bank Experimental Station of Manchester University the largest radio telescope in the world. It is 220 ft. in diameter. It reflects and focuses radio waves just as the great astronomical telescopes focus ordinary light, and it has to be so much bigger, because radio waves are so much longer than waves of visible light. Even so, the Jodrell Bank radio telescope has 10,000 times less resolving power than the big optical telescopes.

One might ask how such an instrument could be of use. It is because the earth's atmosphere is opaque to all electro-magnetic waves, except in two rather narrow bands, one centred in visible light (no doubt the human eye has naturally evolved to be sensitive to a band of waves to which the atmosphere is transparent), and another band centred around the ten-metre wavelength. Besides the big radio telescope, the direction of which is fixed vertically, Lovell uses smaller ones, such as the 30 ft., which is mounted, and can be steered to scan the sky (Plate LVII*b*).

A big radio telescope which could be steered would be a very expensive construction. Nevertheless, a huge steerable radio telescope which can scan the whole sky is being designed and constructed for erection at Jodrell Bank. It will consist of a paraboloid aerial 250 ft. in diameter, rotating on a platform 310 ft. in diameter. The total weight will be 1,270 tons, and elevating racks from old battleships will be used for orientating the telescope.

As smoke and cloud do not disturb observation with radio telescopes, radio astronomy may enable Britain to regain a prominent place in observational astronomy, which had been lost during the last hundred years to countries which could provide very clear skies on mountain tops.

The first great post-war results came from the radar observations of meteors. About 8,000 million of these fly into the atmosphere every day. They are particles of dust, entering the atmosphere at about 100,000 miles an hour. They are difficult to observe by visible light, because of cloud, and the light of the sun and moon.

These are not obstacles to radio waves. Consequently, a continuous

watch on meteors can be kept up by radar day and night. It has already revealed that the intensity of meteors is far greater in summer daytime than at night. Besides revealing many times as many meteor streams as were previously known, radio astronomy has conclusively proved that all meteors have orbits within the confines of the solar system. It seems certain that some meteor streams are associated with comets, and others with minor planets, the meteors being debris of such objects.

In 1945 Hey turned his equipment on to the waves first observed by Jansky. He found that the waves seemed to come from the direction of the stellar constellation Cygnus, and suggested that they might be due to a variable source of radiation in that region.

Then, in 1948, Bolton and Stanley in Australia, and Ryle and Smith in England, began to apply interference methods to the study of these waves from space. These were the parallel in radio with Michelson's methods of stellar observation by the use of interferometers in the range of visible light.

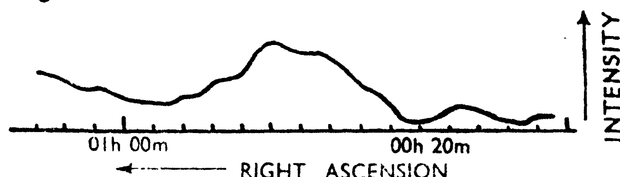


Figure 114. Radio star in the Andromeda Nebula, as seen by the radio astronomer

These investigators have made the tremendous discovery that there are at least one hundred centres from which radio waves are pouring into the earth. In fact, they appear to be a new kind of star, radio stars. There is already evidence that there are as many radio stars in the universe as there are visible stars. Thus by their discovery, they have, as it were, doubled the contents of the universe. Like Galileo, they have revealed a new and unsuspected extension of the universe, and their discovery may well have effects on human knowledge and understanding comparable with his.

In 1950, two of Lovell's collaborators at Jodrell Bank, R. Hanbury Brown and C. Hazard, tilted the 220 ft. giant radio telescope in the direction of the great nebula in Andromeda. They discovered that this nebula, which, though 750,000 light-years away, is the nearest island universe to our own galaxy, is undoubtedly emitting radio waves due to its population of radio stars.

The individual radio stars located by Bolton and Ryle are in our own galaxy, the Milky Way. They have already given new information about the structure of our galaxy. Much of this is blacked out by vast clouds of interstellar dust from visible observation, but fortunately the dust does not obstruct the radio waves.

The observation on the radio stars shows that our local galaxy is a spiral, with the sun situated in or near its arm.

It has been found, too, that radio stars 'twinkle' in a manner exactly analogous to the twinkling of visible stars.

What are these radio stars? Are they ordinary stars in the stage of evolution before they become visible? Are they stars in process of being born, or are they ancient stars in process of dying?

The elucidation of the secrets of the radio stars promises a tremendous new chapter in scientific discovery.

XIX

PHOTOGRAPHY

PROBABLY no group of discoveries and inventions is more familiar through its methods and results than those which enable pictures of the external world to be reproduced faithfully and in any quantity desired. The work of the professional photographer, the picture post-card, the illustrated magazine, are found in every home, and the record of well-loved features, of happy hours, and the contemplation of beauty of form, of light and shade, are available to rich and poor alike. Spare half-hours spent in the cinema open the door to the secrets of nature and annihilate distance by reproduction of scenes from every quarter of the globe. Finally, the enormous growth of photography as a hobby has made hundreds of thousands, young and old, acquainted with the methods of taking, developing, toning, and fixing the impressions which rays of light make upon the sensitive plate.

For the last reason, as well as from considerations of space, no attempt will be made in this chapter to give instructions for taking photographs; but such space as can be spared will be devoted to a description of some of those newer achievements of the science which have, as yet, hardly come within the scope of amateur effort. A brief review of the photographic process for the benefit of the uninitiated will be followed by an explanation of photography in colour, and some applications of the photography of motion.

THE PHOTOGRAPHIC PROCESS

When light passing through a lens falls upon a suitably placed screen, a picture of objects in front of the lens is formed. The same effect can be obtained by passing the light through a pin-hole in an opaque screen, instead of through a lens. The screen upon which the picture falls is of glass, collodion, or paper, and is covered with a thin film of gelatin containing, in extremely fine particles, certain salts of silver. A liquid containing another liquid in such fine particles that a milky appearance

is produced is called an *emulsion*, and the emulsion for photographic plates is prepared by mixing two solutions, containing:

(*a*) Gelatin, ammonium bromide, and potassium iodide;

(*b*) Silver nitrate and ammonia.

A fine precipitate of silver bromide and silver iodide is formed, and when the liquid is poured on a sheet of glass or other material and allowed to dry the particles of silver compound are distributed evenly over the plate.

If the two solutions are mixed in the cold the resulting plate is slow in taking the picture, but still quite fast enough for ordinary snapshot photography. Keeping the first liquid at 120° F. while the second is added produces a plate very much more rapid in action, while if the mixture is kept at 130° F. for an hour there is a further marked increase in the speed. The time required for the light to impress the plate is so small as to be hardly conceivable. In some of the experiments to be described later the exposure is not much more than $\frac{1}{10,000,000}$ part of a second!

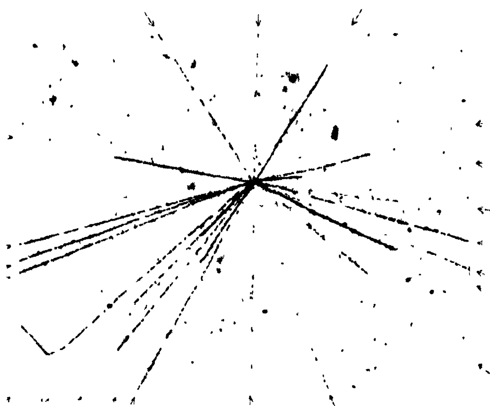
The effect of the light is to decompose the silver bromide and iodide at those points upon which it falls. The lighter parts of the object photographed reflect the most light, and where the image of these falls the greatest amount of decomposition occurs. At first the picture is not visible; it has to be 'developed' by immersion in a bath containing one of the numerous substances sold for the purpose. It is then fixed by immersion in another bath so that light has no further action upon it. The picture, however, is a negative—the light portions of the original are dark in the picture, and vice versa. To obtain a positive, a piece of sensitized paper is placed behind the negative and exposed to light, and the impression is fixed either with or without 'toning'. The latter process consists in soaking in a bath containing a gold or platinum salt, which converts the silver print into one of gold or platinum.

A photograph obtained on a plate prepared in the way described represents only approximately the lights and shades of the original, because the activity of the rays varies with the colour. The plate is affected most readily by blue or violet, and a red object cannot be photographed against a black background. The plate would be affected to a very little greater extent by the red coat of a soldier than by the light coming from a black curtain behind him.

In order to understand not only how this difficulty is avoided but also how others which are dealt with later are overcome, it is necessary to consider the nature of colour. Probably all readers are aware that if a ray of light falls upon a prism, or wedge-shaped piece of glass, it is bent from its original direction, and spread out into a band of colour. Red, orange, yellow, green, blue, indigo, and violet always appear in this order, the last named suffering the greatest deflection (Fig. 115). If the

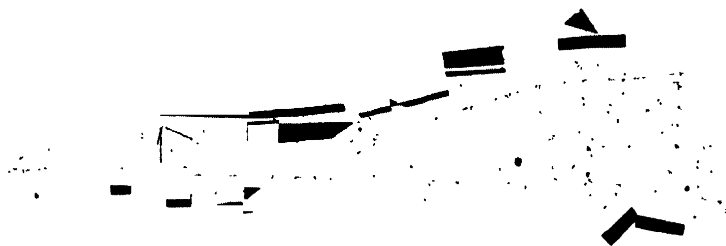


LIX*a*. Waves and eddies in air formed by a bullet



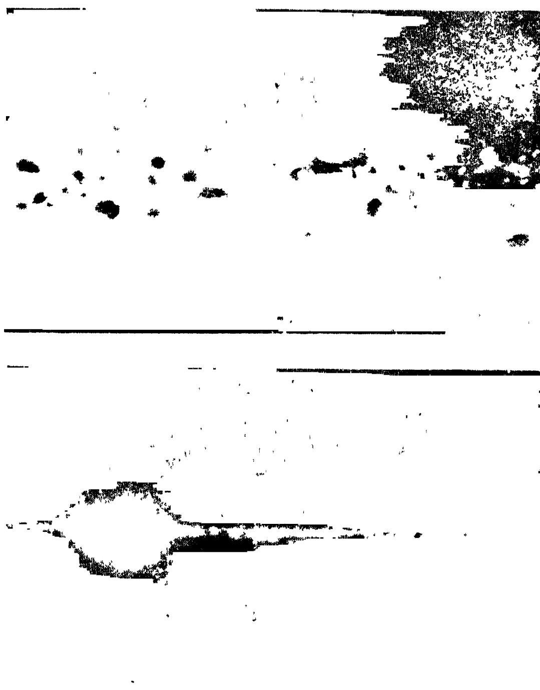
LIX*b*. Explosion of an atom of silver

(*C. F. Powell*)



(*C. F. Powell*)

LIX*c*. The track of a π meson



LX*a*. X-ray photographs of butt welds in mild steel



LX*b*. Scalenohedral crystals of calcite 'dog-tooth spar'



Figure 115. Decomposition of white light

band is passed through a similar prism with its wedge in the opposite direction the colours re-combine to form white light. Or, if each colour is received upon a small mirror so mounted that it can be twisted to reflect the light which falls upon it to the same spot, white light is again obtained.

All the properties of light are explained by supposing it to consist of waves or ripples in a medium which exists throughout all space and in all material things—a medium which can neither be measured, nor weighed, nor detected by any of the senses through which a knowledge of the external world is acquired. A wave of definite wavelength—that is, with a definite distance from crest to crest—produces a narrow line of colour; and a group of waves whose lengths are nearly equal produces a band of colour corresponding to one of those in the spectrum. The smallest waves that produce light are those corresponding to violet, and are no longer than $\frac{3}{10,000}$ of a millimetre or $\frac{3}{254\,000}$ of an inch. The red waves are about $\frac{3}{4,000}$ of a millimetre or $\frac{3}{100,000}$ of an inch in length.

But though these are the only waves which affect the eye, there are larger and smaller waves at either end of the visible spectrum. The former have relatively small photographic activity, but they *can* affect a photographic plate made with a suitably sensitive emulsion. Similarly, a quartz lens coated with a very thin layer of silver is opaque to ordinary light, but allows ultra-violet waves to pass, and permits of a photograph being taken by their aid alone.

The band of colour which can be detected by the eye corresponds, in fact, to a short range of waves which belong to a whole series; and bears much the same relation to the whole of the radiation from a luminous body that an octave does to the whole gamut of a piano. At one end of the series are the short, rapid ultra-violet waves whose length has just been given, which produce no visible effect, but which are exceedingly active in promoting chemical change. From these the series passes

through waves of gradually increasing length until in the infra-red they give rise to all the phenomena of heat. And beyond these are the still longer waves which are used in Wireless Telegraphy.

Now so far as the correct representation of light and shade in an ordinary photograph is concerned, the greater activity of the blue and violet tints throws the picture out of balance, and the problem has been to produce a plate equally sensitive throughout the spectrum. This has been achieved by using a dye, either in the sensitive emulsion or in a screen which is placed between the lens and the plate, which filters the light, and delivers each colour only in such quantity that equal photographic effects are produced in equal times. Such are orthochromatic, isochromatic, and panchromatic plates, which are now obtainable from dealers in photographic materials. For the ordinary purposes of photography the invention of these plates constitutes the most important advance since the introduction of the dry plate. Plate LVI*a* shows the result of photographing the same subject on an ordinary plate (upper), and on a panchromatic plate (lower). It will be observed that not only do some of the brightly coloured calceolarias appear very dark on the former, but the geranium is hardly visible against the background, and the stripes on the petals of the cinerarias are completely lost.

PHOTOGRAPHY OF COLOUR

From the very beginnings of the art of Photography attempts have been made to secure pictures as faithful in their representation of colour as of form and light and shade, and these attempts have been crowned only with a limited amount of success. Of the half-dozen methods which have been devised, that of Professor Gabriel Lippmann stands alone in scientific accuracy. In 1891 he showed that if a sensitive plate

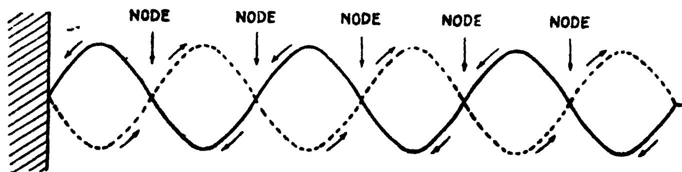


Figure 116. Reflected waves

formed one side of a trough with the gelatin surface inwards, and the trough contained mercury or quicksilver, a photograph of the spectrum and of coloured objects could be obtained. In order to understand how this is effected, it is necessary to consider how the tiny light waves act when they fall upon a reflecting surface.

If a rope is attached at one end to a wall, and the other end is held in the hand, a quick up-and-down movement will send a pulse or ripple along the rope, and when this ripple reaches the other end it will be

reflected. If the pulses are repeated at proper intervals the direct waves will coincide exactly with the reflected waves as in Fig. 116. At equal intervals portions of the rope will be still, and between these there will be portions in violent movement. Just in the same way the waves of light will form within the film layers of rest and of violent movement alternatively, and the latter will be active in causing decomposition of the silver salt. There will thus be formed alternate layers of decomposed and undecomposed silver compound, and the distance apart of the layers will depend upon the wavelength of the light which formed them. For red they will be farther apart, for blue they will be closer together, and for green they will be at intermediate distances. If after fixing, white light falls upon the plates it is analysed by the successive layers in each part of a picture, and only those waves whose lengths coincide with the distance between the layers can escape from the film. All others are suppressed.

The evidence upon which the explanation is based is as interesting as the achievement itself. If the film be warmed by breathing upon it, it expands, and the distances between successive layers are increased. The waves composing white light are now sorted out differently; those corresponding to the original colours are suppressed, and the colours in the picture change. E. Senior and others have cut thin sections of the film and examined them under the microscope. But though evidence of layers was obtained in this way the power of the microscope was insufficient properly to separate them. A more effective proof was obtained by S. R. Cajal, of Madrid, who caused the gelatin sections to swell by placing them in water, and then photographed them under the microscope.

A well-known writer has said that you can fool some of the people all the time, you can fool all the people some time, but you can't fool all the people all the time; and this well describes the advantages and disadvantages of Lippmann's method of colour photography. The spectrum and some objects can always be photographed, but for many purposes the method is, unfortunately, unreliable.

All other processes are based on the Young-Helmholtz theory of colour vision, according to which the human eye is sensitive to only three fundamental colours—red, green and blue. Every tint that can be recognized is composed of one of these or of a mixture of two or all three of them; and all three in certain proportions produce white light. It is therefore necessary to photograph only the red, green, and blue portions of a coloured object in order to secure a picture which represents the original colours so far as they can be detected by the unaided eye.

In 1892 Frederick Ives, of Philadelphia, adopted the plan of taking three photographs through red, green, and blue glass screens respec-

tively, and in 1893 he patented two pieces of apparatus for viewing the pictures so formed. In one of them, the pictures, placed side by side in a lantern with a triple front, were projected on a screen, and by means of a lever, were caused to fall on the same disc. This superposition of the red, green, and blue portions of the photograph gave a beautiful picture quite near enough to the actual tints to satisfy any but the most captious critic.

Joly, of Dublin, devised a screen covered with a very large number—350 to the inch—of red, green, and blue lines ruled in dyes on a glass plate. Each line had to be in contact with the one on either side of it and there had to be no overlapping. The photograph was taken and viewed through the same screen. The lines were so narrow that they could only be detected by close inspection. At a little distance they merged into one another and individual colours were lost.

A screen of this kind with 600 lines to the inch has been constructed by T. H. Powrie and Florence Warner, of Chicago, and it is known commercially as the Florence plate. The method is extremely ingenious. Lines about $\frac{1}{300}$ of an inch wide are ruled in black ink on a glass plate with spaces $\frac{6}{100}$ of an inch in width. A plate covered with a film of gelatin containing bichromate of potash is exposed under this screen, and where the light falls through the spaces the gelatin is rendered insoluble in warm water. The plate is then washed, fixed, and dipped in green dye, which is absorbed by the fine gelatin line which remains. Another film of bichromated gelatin is run over the plate, and a second exposure made with the black line on the screen covering the green line. This leaves a narrow line of the new gelatin exposed. The plate is treated in the same way as before, but with a red dye. There are now green, red, and colourless lines on the plate. A fresh film of gelatin is run on, a further exposure made with the black lines covering the green and red lines. The third line is now stained blue, and a Joly screen is produced with lines only about half as wide.

In the autochrome process, three quantities of starch are stained with red, green, and blue respectively, and then intimately mixed so that the colour of the mass is neutral. But if a few of the minute grains of which the starch is composed were examined under the microscope, they would be found to be transparent globes of red, green, or blue according to the original batch from which each had come. The dry grains are dusted over the plate in a single layer and pressed, or else the spaces are filled in with a fine black powder. The layer is secured by a waterproof varnish, and the sensitive emulsion is poured over the top, thus forming plate and screen in one. The smallest detail in a photograph which is visible to the naked eye will be covered by a multitude of grains of all colours, and whatever the colour of the original may be, sufficient light passes through the appropriate grains to affect the plate.

Another very interesting method is that of the Paget Prize Plate Company, to whom the writer is indebted for information. The screen is in this case separate from the sensitive plate, and is covered with a number of minute squares of red, green, and blue. It is prepared by coating a clean glass plate with a special collodion, which is then stained with a red dye. Portions of the plate are then coated with a 'resist', after which it is placed in a bath and the uncoated portion bleached. It is then placed in a green dye, which replaces the red which has been dyed out. A further series of 'resist' squares is printed on the plate, and the uncovered green is bleached. Finally, the plate is re-dyed with blue. The result is a finished screen with all its colours in one plane, without any overlap, and no white or black. Very effective copies for viewing directly or by the lantern can be made, and all kinds of coloured objects can be faithfully and brilliantly reproduced.

A most important application is the production of the beautiful coloured illustrations which appear in modern books and magazines. The process is based on that of Ives. Three photographs are taken of an object or scene, and a block is made from each. When these blocks are stained with ink of the requisite colour and impressed in succession on the paper, the object or scene is reproduced in colours strikingly near to the original. The trouble of taking three separate photographs is sometimes avoided by using in the first instance a Lumiere plate. The three blocks are then made from the same photograph by interposing appropriate screens.

THE PHOTOGRAPHY OF MOTION

Not many people are aware that the first step towards the photography of a succession of movements were taken as long ago as 1872. In that year Muybridge, a Californian, obtained twenty-four successive photographs of a trotting horse. His plan was to arrange twenty-four cameras in a line opposite a white screen. Stretched between each camera and the screen was a thread, and as the horse passed it tightened and broke the thread, and in so doing operated the shutter of the corresponding camera.

In 1882 Marey, of Paris, constructed the beautiful apparatus known as Marey's pistol. It was, indeed, very like a revolver, but the drum which in the fire-arm carries the cartridges, in this case carried a circular glass plate coated with sensitive emulsion and wholly enclosed. The only direction from which light could reach it was down the barrel. When this pistol, charged with its sensitive plate, was pointed at any object, and the trigger pulled, the plate rotated about its centre in a succession of jerks, and as it paused for a moment after each step a photographic impression of the object was made near the rim.

No real advance in the photography and reproduction of motion was possible until improvements in the manufacture of celluloid provided a long thin strip of sensitized material upon which a succession of many pictures could be obtained. The stimulus which led to this was the need for a film to replace glass plates in a magazine camera, thus reducing the weight and permitting a larger number of snapshots to be taken. And when success was attained there was one man at any rate—Thomas Alva Edison—who was ready to take advantage of it. At the World's Fair at Chicago in 1893 machines were exhibited which worked upon the penny-in-the-slot principle. A nickle was dropped into a machine, and with eyes glued to a small opening the observer saw for about half a minute a complete set of movements illuminated by a small electric lamp.

The principle of this and all later machines is that an image thrown upon the retina—the wonderful screen at the back of the eye—persists for about a tenth of a second after the stimulus which produced it has passed away. A picture can be formed on a photographic plate far more rapidly than this, and the number of pictures that can be taken in a second is only limited by the speed at which a shutter can be made to flash the light upon successive portions of the film as it is wound rapidly from one roller on to another. For all ordinary purposes it is sufficient to take sixteen photographs a second and submit them to the observer at the same rate.

It does not seem to have occurred to Edison to project the pictures on a screen, and the subsequent development of moving pictures as we know them today is mainly due to R. W. Paul, the scientific instrument maker. According to F. A. Talbot, Edison did not patent his invention in England, and Paul's attention was drawn to the matter by a man who asked him to make films for him. The possibility of projecting them by means of a lantern soon appeared, and one night in 1895 the attention of the police was called to loud cries proceeding from a building in Hatton Garden. On entering they found that what they had suspected to be a grim tragedy was a joyful demonstration which attended the first successful attempt to show moving pictures on the screen. The show was repeated for their benefit, and they were the first persons other than Paul and his assistants to become familiar with the new invention.

The cinematograph is a mechanical device for obtaining the movement of the film. This is 1½ in. wide, and is pierced with holes along both edges. The teeth of wheels something like chain wheels and called sprockets, fit into these holes and control the movement. At first this was continuous and a rotating shutter in front of the lens allowed each picture to fall upon the screen for a short time, but the best effect is obtained by intermittent motion by which each picture is allowed to come to rest before it is disclosed by the shutter.

The manufacture of films has become an enormous industry. They are developed and fixed in special machines which pass them through the necessary baths and dry them. They are then copied and dispatched to the cinemas.

Not the least interesting records are those which have been obtained of the habits of animals, and the growth of plants. To secure the former the haunts of beast and bird have been invaded, and the camera has penetrated the dark recesses of the tropical forest where formerly a gun would have been regarded as the only weapon that could safely be used. In registering very slow motions such as the transformation from caterpillar to chrysalis, and chrysalis to butterfly, the growth of a plant, or the unfolding of a flower (Plate LVIII*a*) photographs are taken at long intervals and then thrown on the screen in rapid succession. Many of the trick pictures in which, for example, a knife cuts up a loaf of bread and a sandwich is made without visible hands, are the result of a large number of separate photographs in which the setting is changed between each, the film being covered meanwhile by the shutter.

It was hardly to be expected that inventors would be satisfied with pictures in black and white, and some of the earlier films were coloured by hand. But when longer films came into vogue this was too expensive, and instead of painting in each picture by hand, stencils were adopted, and though the same amount of delicacy was not possible, there was colour. But even this process soon became expensive with a film 1,000 ft. long containing more than 12,000 pictures.

As early as 1899 a method was devised by Greene, whereby the photographs were taken through red, green, and violet screens and flashed on the screen successively through screens arranged in the shutter. But while sixteen a second is sufficient for black and white, a three-colour process of this kind requires forty-eight pictures a second, and there were mechanical difficulties in securing this. The film must be panchromatic, and can only be developed in darkness.

The difficulties of a three-colour process led Albert Smith to propose two colours only—red and green. The method was patented in 1906, introduced commercially in 1907, and improved in 1911. This is the famous Kinemacolour process. Pictures are taken alternately through red and green screens, and projected through a rotating disc having two opaque sectors, one transparent red and one transparent green sector. Blue is not entirely absent owing to the green containing a little, but indigo and violet are not reproduced, and the reds and greens are emphasized.

SOME SCIENTIFIC APPLICATIONS

If one wishes to know something of the fidelity and speed of the modern photographic plate the greatest achievements will be found in

the laboratories of scientific workers, who use the camera to record observations that the eye cannot distinguish nor the mind, without difficulty, conceive. The tiny bacteria, those low forms of vegetable life, some not more than $\frac{1}{25,000}$ of an inch in diameter, which exercise a powerful influence in health and disease, are photographed with ease. A minute drop of the liquid or slice of the jelly in which they are cultivated is placed on a glass slide under a high-power microscope, and the image, hundreds of times larger than the object, is thrown upon a sensitive plate. When this is developed the investigator has a record which he can examine at leisure and use for comparison without undergoing the strain that microscopic observation involves.

The special services which the microscope and the camera render to the steel maker and the engineer have been detailed in Chapter VIII. With their aid the minute internal structure of metals is revealed and permanently recorded. In association with the chemist, the microscopist and the photographer have built up during the last fifty years a body of knowledge that exercises an influence upon the most delicate instrument of precision, and the most gigantic structure conceived and erected by the engineer. The tiny waves of light falling on the polished or etched surface of a piece of steel reveal those variations of level which are due to the varying hardness or chemical composition of the constituents. And the examination of samples of proved strength and reliability affords a standard by which untried materials can be judged.

Some of the most remarkable results in the photography of bodies in motion have been obtained at the Marey Institute in Paris, which was established to continue the methods of inquiry—mainly, in physiology and medicine—to which E. G. Marey had devoted his life. From the numerous investigations which have been carried on at this institute, two are selected for notice—one in which the objects studied are extremely minute, and the other in which the movements are extremely rapid.

In few subjects has such remarkable progress been made in recent years as in the study of diseases—particularly those which are due to living organisms. While many diseases are caused by the tiny members of the vegetable world called bacteria, others have been found to be due to equally minute forms of animal life called *trypanosomes*. A particular organism found in the blood of patients when suffering in a particular way, and at no other time, is assumed to be the primary cause, and a cure can only be found by a study of the organism itself.

Blood is a colourless fluid containing myriads of microscopic particles called corpuscles—red and white—so small that in $\frac{1}{20,000}$ of a cubic inch there are nearly 5,000,000 of the former and 6,000 of the latter. To the red corpuscles the blood owes its colour, and they serve to carry the oxygen round the body and to remove the waste products that are formed in the tissues. The function of the white corpuscles

remained for many years a mystery, until it was found that they waged war upon the germs of disease. Neither the red corpuscles nor the *leucocytes*, as the white corpuscles are called, are living creatures, and the leucocytes act as though they suffocated or poisoned such of their enemies as became entangled within their substance.

Such facts as these have been established by patient and laborious work with the microscope—work which has often had to be conducted in those unhealthy districts in the tropics where disease is rampant, and its causes present in overwhelming array. The application of photography was not so simple as it appears at first sight, because the germs are extremely sensitive to light and heat; the concentration of radiant energy upon the drop of liquid or jelly in which they grew in the beam from the lamp was often sufficient to kill them in a few seconds, leaving nothing but their dead bodies for examination. The heat could be cut off by interposing a trough of water, but the transparency of the objects rendered them difficult to observe, dead or alive, and often it was necessary to kill them and stain the remains so that they could be more easily examined.

The use of photography is of great value in obtaining a record which can be examined and compared with others at leisure; but it only represents a momentary glance, as it were, and can only be supplementary to continuous and persistent observation. For these small objects are in constant movement; they are increasing or decreasing, creating great changes in the liquid or jelly in which they are immersed, and entering into conflict with leucocytes if present in blood.

The investigator requires exact information on these matters, and more particularly he desires to study the behaviour of these organisms in the presence of various substances, amongst which he hopes to find a cure. And to these ends he has called in the services of the cinematograph. After many experiments G. Comandon, working in conjunction with Messrs. Pathé Frères, succeeded in obtaining records which enabled the processes to be examined over and over again, on a scale thousands of times greater than the actual size. The portion of a film can be projected on the screen so that it is magnified sixty times; and as the pictures on the film itself are already 400 times larger than the actual size of the objects, the total magnification is some 24 thousands.

In these investigations the difficulties which had to be overcome arose almost entirely from the minute character of the objects whose movements it was desired to record, for the slightest vibration would throw them out of focus. But in the experiments on the flight of insects, by M. Lucien Bull, now to be described, the objects were large enough to require little or no magnification, but their movement was so rapid that not even a revolving shutter would permit of a sufficiently short

exposure. Instead of one-sixteenth of a second, the pictures had to be taken at intervals of a few thousandths, and for this purpose a series of electric sparks had to be employed.

The general arrangement of the apparatus is shown diagrammatically in Fig. 117. The sparks are produced by an induction coil A, and occur between two poles of magnesium at E. This metal produces a light very rich in ultra-violet rays, and therefore enables an effect to be obtained on a photographic plate or film with a very short exposure. The film is fixed to the rim of a drum R which is rotated at high speed by an electro-motor. The drum is enclosed in an octagonal box upon one face of which are fixed the lenses. D is a small window the light from which is reflected towards the insect by the mirror M. For as the work has to be done practically in the dark, there must be some means of controlling the direction of flight, and advantage is taken of the fact that all insects fly towards the light.

The 'make-and-break' of the coil is not accomplished by a vibrating spring but by a rotating interrupter I, fixed on the shaft of the drum. This ensures a definite number of sparks, and therefore a definite number of impressions, per revolution. Ordinarily the insect appears in the picture as a silhouette, and parts of the wings which it may be desired to observe are not easily seen owing to the flatness of the picture. But Bull avoided this by arranging a stereoscopic front combined with an ingenious shutter device which enabled him to take pictures showing proper perspective.

The spark-gap is one millimetre long, and the number of sparks 2,000 per second. The diameter of the drum was 34·5 cm., or about a foot, and with a film 1·08 m., or a little over 3 ft., long it is possible to obtain fifty-four successive pictures of the usual cinematograph size. The speed of the film was 45 ft. a second, so that the total time during which the movements of the insect could be recorded was one-fifteenth of a second. In view of the rapid movement of the wings this is amply sufficient to enable a detailed analysis to be made.

Dragon flies and house flies were held in a pair of tongs shown at A in Fig. 118. The limbs tend to fly apart, but are prevented by a small catch. On closing the circuit, which includes the electromagnet and the shutter (S in Fig. 117), the insect is liberated and at once commences its flight. As all insects become sluggish during confinement they have to be used in a fresh condition, or they do not start at once. But while this method is satisfactory for the insects mentioned, a different plan has to be adopted for hymenoptera, such as bees and wasps, which hesitate for a moment before taking flight. The one finally adopted for these is shown at B, Fig. 118, and consists of a glass tube about 2½ in. long and wide enough to allow the insect to crawl through it easily. The front is closed by a light flap of mica attached to the end of a metal arm which

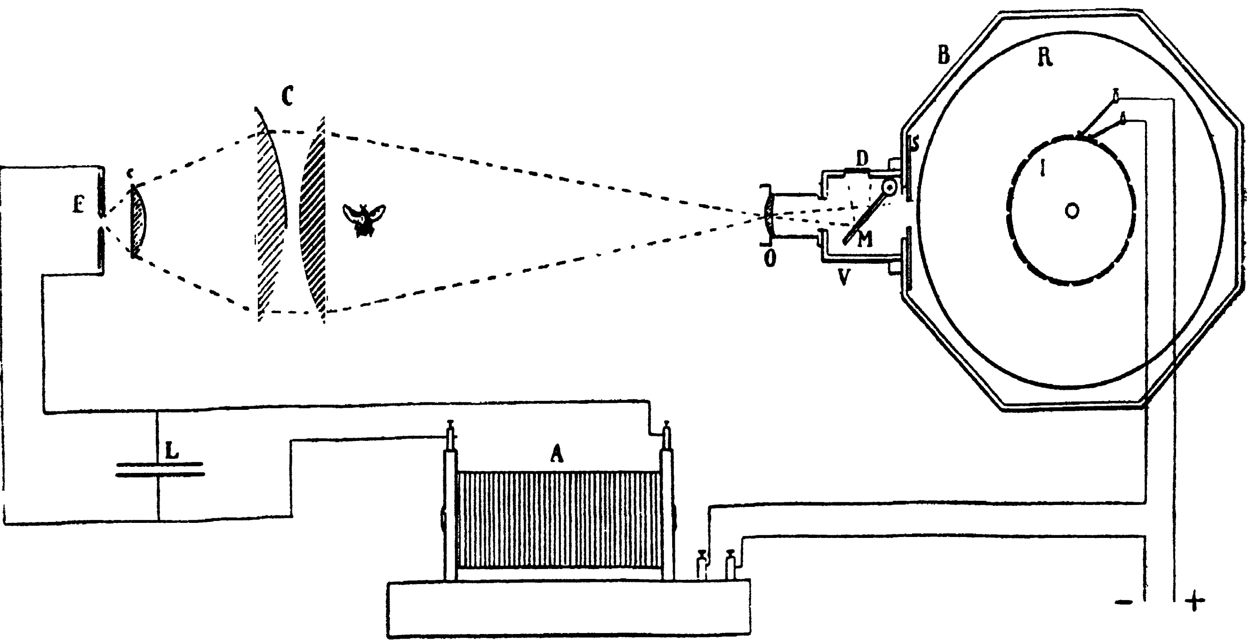


Figure 117. Diagrammatic arrangement of apparatus for obtaining cinematographic records of insects in flight

closes the circuit between the two metal bands. The circuit is first broken by a switch, then the insect is introduced. As it lifts the flap in crawling out, the switch is put on, and as the insect flies, the flap falls, completes the circuit, and operates the shutter.

For insects belonging to the coleoptera, such as beetles which hesitate for a still longer time, a third form of release had to be provided. This (see C, Fig. 118) consisted of a lever pivoted at the centre of a similar tube, along which the insect crawls. The hand switch is first broken,

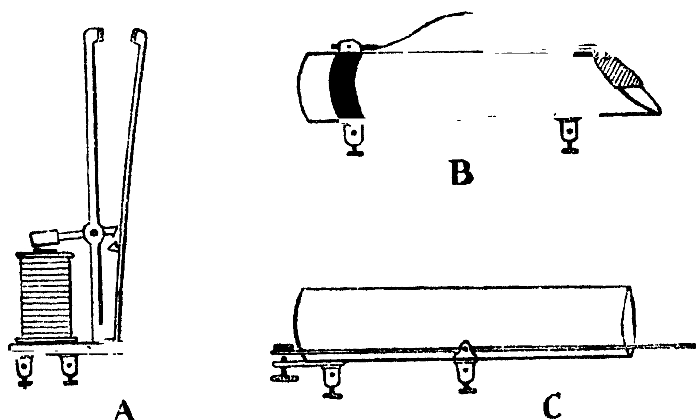


Figure 118. Apparatus for holding and releasing different species of flying insects

then the insect is introduced. During the first half of its journey it presses the back end of the lever upon the contact, and when it passes the centre the lever tips up. The hand switch is now put on, but the shutter cannot act until the insect rises from the front end of the lever and allows the back end (which is the heavier) to fall. In this way the insect unconsciously 'pulls the trigger' which enables the picture to be taken.

Perhaps the most remarkable examples of accuracy and delicacy of the photographic record, however, occur in connection with investigations of the flight of projectiles and the adjustment of firearms. About sixty years ago C. Vernon Boys employed an electric spark to obtain photographs of flying bullets. They were fired from a pistol, and caused two wires to come into contact, whereby a circuit was closed, and a spark occurring at another gap, a silhouette was obtained on a photographic plate. In this way the various effects produced by a bullet striking and penetrating a glass plate were recorded. At the first contact the surface of the glass was powdered; then a rounded disc was forced out,

and only after the bullet had emerged on the other side did the plate shiver and crack.

Incidentally it was observed that certain black lines appeared in the photograph which corresponded to no visible part of the apparatus. These turned out to be waves in air similar to those which a ship makes in moving through water. They form a V with its apex a little in front of the nose of the bullet, and if an obstacle such as a piece of wood or glass is placed so that one of the limbs impinges upon it, the wave is reflected exactly in the way that theory predicts.

It is interesting to note in this connection that about six or seven years later, R. W. Wood, of the Johns Hopkins University, Baltimore, extended these experiments to the instantaneous photography of waves of sound. Two spark-gaps were arranged, so that while the crack of one caused the aerial disturbance, the other cast a shadow of the wave on a photographic plate. By increasing gradually the interval between the two sparks he was able to trace the wave in ever-expanding circles, just like the ripples in the surface of water when a stone is thrown into a pond. He followed the wave through a small hole in a screen and showed that the wave front beyond formed the surface of a sphere, and similar results were obtained when two or three perforated screens were placed in line. And finally he showed the reflection of the wave at plane, spherical, and parabolic surfaces.

Plate LIX*a* is from a photograph by Mach of the air-wave produced by a bullet in full flight. The eddies in the wake are very noticeable, and may be compared with the photograph of water flowing past an obstacle in Plate XLII. It will be observed that the apex of the waves causes the bullet to exert an effect before it actually touches an object. In some experiments the spark is produced by the bullet breaking a thin strip of copper stretched across its path, and it has been shown that the strip is broken by the air-wave. The bullet and strip do not come into contact. When the method of making the bullet or projectile produce its own spark or series of sparks had been devised, the next step was to record successive movements on a film, and this was accomplished by J. Athanasiu in 1903. But remarkable experiments in this direction were made by C. Cranz of the Berlin Academy of Military Technology, who employed a variety of methods (Plate LVIII*b*).

So far as slower motions are concerned, a series of sparks can be obtained at regularly recurring intervals by the rotation of a wheel with a number of metal strips on the rim, which come into contact with a fixed metal brush and discharge a battery of Leyden jars. But for motion of the greatest rapidity, an apparatus like that employed in wireless telegraphy is used, which gives a series of sparks at intervals corresponding with the natural period of electrical vibration of the circuit.

But Cranz's greatest achievement was that of obtaining a cinematographic record of the whole process of firing a gun, including the flight of the bullet through the air and through various obstacles. The apparatus is shown in diagrammatic form in Fig. 119. An alternating-current generator supplies electricity to a transformer, which is connected to the terminals of a spark-gap placed in front of a large concave mirror. Between the generator and transformer is a pendulum-break, shortly to

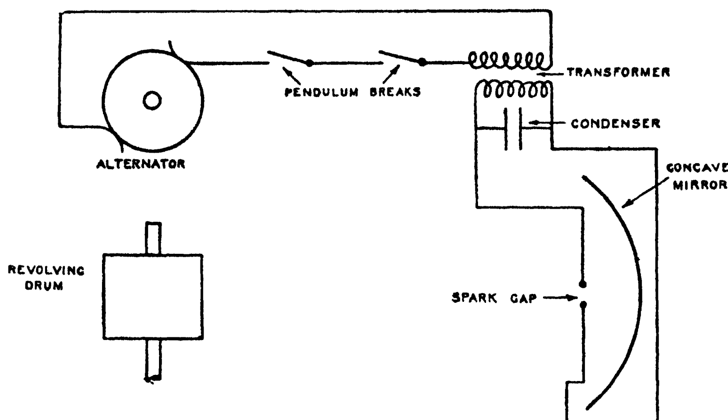


Figure 119. Cranz's apparatus for cinematography of flying bullets

be described, and between the transformer and the spark-gap is a condenser which gives capacity to the secondary coil of the transformer and determines its period of vibration. Opposite to the mirror is a steel roller, carrying a film, which can be rotated at a regular and known speed. It is 50 cm. (nearly 20 in.) in circumference, and 28 cm. (about 11 in.) long, and the speed of rotation can be so great as to give the film a velocity of 140 m. per second. This in British units is 420 ft. per second, or nearly 300 miles an hour. Usually the velocity is 90 m. or nearly 280 ft. a second, or about 180 miles an hour. Even this velocity is three times the speed of an express train and one-fifth of the speed of a bullet as it leaves the muzzle of a rifle.

The pendulum-break which has been mentioned consists of a metal pendulum which is held up or released by an electro-magnet. Below it are three curved rods of metal, each of which carries a contact piece. When the experiment is ready the pendulum is released by a hand switch, and operates the contacts in succession. The first contact fires the gun, the second starts the sparks, and the third stops them. The sparks follow one another at the rate of 5,000 a second, and each spark produces a picture, so that 500 pictures can be taken in a tenth of a

second, with the alternator making 2,500 alternations per second. Machines have, however, been built which give 50,000 alternations and therefore 100,000 sparks per second.

A bullet fired into a suspended bone from a pistol with a small charge drills a hole clean through without breaking it. The effect of a shot from an infantry rifle with a full charge is a complete shatter of the bone *after* the bullet has passed through. Pictures show the powdering up of the bone and the projection of the particles backwards, as the bullet enters. When the bullet has passed out of the field of view the bone begins to splinter up, the shock evidently requiring an appreciable time to act upon the particles of which the bone is composed.

Photography is employed to record continuously all those changes about which man desires information, in cases where personal observation would be neither so continuous nor so infallible. The varying height of the barometer, the temperature, the duration of sunshine, the changes in temperature and volume within the cylinder of an internal-combustion engine, tremors in the earth's crust, and the rhythmic beat of the human heart, are capable of being registered on a roll of sensitized paper.

PHOTOGRAPHIC PLATES FOR ATOMIC RESEARCH

A development of an old device has led to the most important discoveries made in experimental atomic physics since the end of the Second World War. This is the adaptation of photographic plates for following the movements of atomic particles. Ordinary photographic plates have been used for this purpose, and indeed, the original discovery of radioactivity by Becquerel in 1896 was due to the fogging of plates by radiations from uranium, which consisted in part of atomic particles.

When a charged atomic particle passes through a photographic emulsion, it affects the silver halide grains along its path, and, like a ray of light, changes them so that they can be made visible by treatment with a developer. This causes them to appear as black specks of silver, which can be seen under a microscope. The track of the particle is revealed by a trail of specks, like that of a runner in a paper-chase.

Ordinary photographic emulsions were invented for registering rays of light. It is not surprising, then, that they were found not to be particularly suitable for registering the tracks of particles, and many early experimenters gave them up after the first trials. The idea of using the photographic emulsion seemed so attractive but gave disappointing results.

Presently, it was tried once more by C. F. Powell at Bristol. He decided to make a systematic investigation of the technique. Instead of trying to use plates, he aimed at evolving new kinds of photographic

emulsions specially made, not for ordinary cameras, but for registering atomic particles. He conducted the physical side of the research, while Ilford Ltd. collaborated closely with him in making the new emulsions. It was found that their constitution should be very different from those of ordinary emulsions. They should contain very high concentrations of silver halide. They should also be much thicker than ordinary photographic emulsions, so that the particle could travel further without escaping from the emulsion. These differences required new methods of developing.

After some years of work Powell and Ilford Ltd. revolutionized the possibilities of the photographic plate technique for nuclear research. The improved emulsions revealed numerous phenomena, caused by the particles, which had not previously been visible. Powell worked out the technique of interpretation of the pictures of tracks and their physical meaning.

In Plate LIX*b* the tracks of twenty-five particles shot out of the nucleus of a silver atom are shown. The silver nucleus has been exploded by a cosmic ray particle of very high energy. The characters of the tracks show what kind of particles have made them. In this picture, the tracks of protons, α-particles, and heavier nuclei can be recognized.

Many years ago, Anderson discovered that cosmic rays contain a particle about 200 times as heavy as an electron, and that the very penetrating cosmic rays consist mainly of them. The theory of particles and radiations suggested that these new particles, now called mesons, ought to exist for only a very short time, and then decay. Powell secured photographs of such an event. In Plate LIX*c* the track of a π-meson is seen ending near the bottom of the photograph. Emerging from its end is a μ-meson, which has shot back and has finally escaped from the confines of the emulsion.

It is thought that mesons are produced by the passage of very fast cosmic ray protons and neutrons through the nuclei of atoms. Consequently, the behaviour of mesons may reveal the nature of the fundamental forces inside the nucleus of the atom. Thus the new photographic emulsion technique of studying fundamental particles has become the most powerful instrument of the day for investigating the inside of the atom, the very heart of nature.

XX

THE ATOM

THERE are certain periods in the history of science when a discovery or group of discoveries alters the whole trend of thought. Of such a nature are the discoveries which have risen out of a study of the properties of radium.

In order to give some idea of the nature and meaning of radioactivity it will be necessary to pursue several lines of enquiry, and afterwards to correlate them.

THE DISCHARGE OF ELECTRICITY THROUGH GASES

Air and other gases are, at ordinary temperatures, and when dry, non-conductors of electricity. In order that a spark may pass between two balls one inch apart in air, an electromotive force of something like 100,000 volts is required.

A highly rarefied gas conducts more easily. If it is contained in a tube which can be gradually exhausted, the electrodes by which the alternating current from an induction coil enters may be placed several inches apart. At first there is no discharge, but as exhaustion proceeds a broad band of light appears between the electrodes, which, as the pump is worked, widens until it fills the tube. The colour depends upon the nature of the gas. At one stage there is a flickering appearance owing to the concentration of the light in thin layers which fill the tube from end to end.

As the vacuum becomes higher a dark space forms round one of the electrodes—called the cathode—and this space increases as the quantity of gas in the tube becomes less, until it fills the whole tube, the walls of which glow with a faint greenish light. Finally, when the exhaustion is pushed to the fullest extent the electricity refuses to pass, showing that the gaseous matter originally in the tube was necessary to convey electricity through it.

The broad band of light first formed is produced when the pressure

falls to about 10 mm. of mercury; the striæ or flickering layers are most brilliant at 3 mm.; while the dark space fills the tube at about 0·03 mm. There is then present less than $\frac{1}{25,000}$ of the amount of air required to fill the tube at atmospheric pressure.

From the middle of last century these effects excited considerable interest, and many beautiful experiments were devised. Hittorf placed a small mica cross in the tube in front of the cathode, and found that the end of the tube covered by the cross did not glow. This indicated that something was projected from the cathode which travelled in straight lines.

Crookes was led to the view that matter in a fine state of division, such as the attenuated gas in the tube, possessed special properties, and he gave to it the name 'radiant matter'. He showed that if a magnet was held near the tube the stream of particles could be bent out of its original direction.

This deflection is just what would occur if the stream were composed of tiny particles carrying charges of negative electricity. Such a stream would be equivalent to a current of electricity. P. Lenard constructed a tube with a thin aluminium window at the end opposite to the cathode, and found that the rays would penetrate it. Outside the tube they caused a cloud to form in moist air, and, by rendering the air a conductor, discharged an electroscope.

It may be well here to devote a few words to the gold-leaf electroscope which, while one of the simplest and commonest pieces of electrical apparatus, has proved in relation to radioactivity to be one of the most delicate instruments of research. It consists ordinarily of a pair of strips of gold leaf attached to the bottom of a metal rod. This rod is fixed by means of paraffin wax, ebonite, or other non-conductor in the neck of a flask, or in the top of a box with glass sides. A good type for ordinary purposes is shown in Fig. 120. A more suitable form for measurement is one in which the rod terminates in a metal plate, and a single strip of gold leaf is attached at the top edge so that it hangs as a hinged flap.

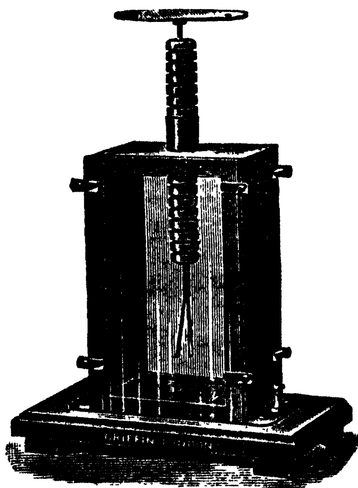


Figure 120. Chattock's gold-leaf electroscope

When the instrument is electrified the leaf is repelled from the plate, and falls as the charge leaks away. A graduated scale enables the rate of

loss of charge to be measured by the rate at which the leaf falls, and this gives a measure of the conductivity of the air.

J. J. Thomson and his pupils proved that these 'cathode rays' produce the same effects whatever the gas in the tube. By an ingenious arrangement J. J. Thomson measured the mass of the flying particles which compose the stream, and showed that in all cases they were about $\frac{1}{1,700}$ of the weight of a hydrogen atom. More recent measurements give the fraction as $\frac{1}{1,845}$. They are projected from the cathode with a velocity comparable with the speed of light, and as the results are always the same whatever the gas in the tube the conclusion is inevitable that the radiant particles are common to all matter. In 1897 J. J. Thomson advanced the view that these *electrons*, as they are called, are actually present in the atom—that a group of electrons, in fact, composes the atom—and that they are torn off during the passage of the electric current.

X-RAYS

In 1895, W. C. Röntgen was using one of the tubes which have been described when he found that some photographic plates which were in a drawer in the bench were fogged. From this he was led to the discovery of the X-rays which are produced by any solid body when it is bombarded by a stream of radiant matter or electrons. Usually a disc of metal is mounted centrally in a bulb, and the electrons are directed upon it by passing an electric discharge through the bulb. The rays affect a photographic plate, cause many substances to *fluoresce* or shine with a light of characteristic colour, and discharge an electroscope. They are absorbed to a greater extent by dense substances than by light ones, passing readily through paper, flesh, etc., but with less ease through bone and metals. This difference of penetrative power rendered them of immense value in surgery. When they were passed through the hand, arm or thinner parts of the body a shadow of the bones and of any denser substance such as a ring or an embedded needle, was cast upon a fluorescent screen or a photographic plate beyond.

The most effective form of tube is that invented by Coolidge. It possesses three special features: First a high exhaustion rendered possible by the more effective air-pumps of the present day (see p. 360). Secondly, a heavy tungsten anode, which will withstand severe electrical bombardment without fusing. Thirdly, a coil of tungsten wire as cathode which can be heated by a separate current and emits the electrons necessary to render the space conducting. The wire is surrounded with a molybdenum tube or hood to focus the cathode stream on the anode.

With modern apparatus the whole body can be photographed, and important discoveries with practical results have been made. Thus the

alimentary canal, or tract through which food passes and which extends the whole length of the body with many twists and turns in the intestines, has been rendered visible. This is accomplished by giving the patient a meal of bismuth carbonate—say 2 oz. of the carbonate in 10 oz. of porridge, which is so opaque to X-rays that a shadow of the tract as the food passes through it may be thrown upon the plate. It is found that local disease of the canal is accompanied by general trouble—you cannot have a clean stomach and appendicitis at the same time. Another valuable application is to a joint such as the knee, for it is possible to discover at an early stage the existence of tubercular disease.

Perhaps an even more striking example of the increase in penetrative power is furnished by its use in engineering and metallurgy. Flaws in forgings and castings and imperfect welds in joints can readily be detected provided the metal is not more than say two inches in thickness. Plate LX*a* is an X-ray photograph of a butt weld in mild steel and shows blow-holes due to ineffective workmanship.

The rays consist of short trains of waves, or pulses, produced by the impact of the electrons upon the anode. And just as waves of light enable us to investigate the structure of bodies through which they pass—just as they enable us to picture the mechanism of refraction, dispersion, and polarization—so also the more minute wavelets in the X-rays provide us with an instrument of surpassing delicacy for the discovery of secrets which the grosser light rays fail to reveal. To understand how this is accomplished we must first explain.

THE PHENOMENA OF DIFFRACTION

Though the statement that light travels in straight lines is true so far as propagation in a continuous medium of uniform density is concerned, it *does* bend round the edge of an opaque object, and the larger the waves the greater is the bending. The red rays are bent more than the yellow, the yellow more than the green, the green more than the violet. This explains why an opaque object held between the eye and a distant source of light appears to be bordered by a coloured fringe. Each of these is a small spectrum, but the colours are so close together that they cannot be clearly distinguished. The same effect is observed when light coming from a narrow slip is examined.

Now suppose that light of one wavelength only issues from a slit and then by means of a lens passes as a parallel beam through a number of slits formed by ruling, say, 6,000 to 14,000 lines with a diamond on a glass plate. If the light from this grating, as it is called, is focussed on a screen, bending will cause the rays to travel different distances from the slits to reach any one line on the screen. When two waves which have travelled distances differing by half a wavelength (or any odd number of

half wavelengths) fall on the same line, the crest of one will coincide with the crest of the other, they will be mutually destroyed, and that line on the screen will be dark. But if the waves differ by a whole wavelength (or an even number of half wavelengths) crest will coincide with crest, trough with trough, they will reinforce one another and there will be light on the screen. We shall have, therefore, alternate bands of light and darkness, and as each slit has two edges these will be arranged symmetrically on each side of a centre line formed by the light which passes directly through the slit.

If the experiment be repeated with white light, each of the bright lines will be broadened into a band of colour, and these bands are spectra. Because they are produced by diffraction at the edges of slits they are called diffraction spectra, and they are said to be of the first, second, third, etc., order according to their position with reference to the centre line. They become fainter as they become more remote.

The phenomena have so far been studied as occurring in a regular way, but there are many cases in nature in which diffraction occurs by light waves striking small particles and becoming 'scattered', which is only another way of saying that they are bent in various directions. Thus, when a beam of light passes through a smoke or dust-laden atmosphere, or through a liquid in which small particles are suspended, the track of the beam can easily be seen by looking at it at right angles. The amount of scattering depends upon the wavelength and the size of the particles. Short waves are more freely scattered than long ones, and the blue of the sky, which is always deepest at right angles to the sun, is due to the scattering of short waves by the small particles in the atmosphere. The particles which will effect this are too small to be seen by the naked eye, so the fact that scattering occurs furnishes information as to a structure which is invisible. In Chapter XI it was explained how this method has been used to detect the presence of particles beyond the range even of microscopic vision, and the actual existence of which has only been proved in recent years by the ultra-microscope.

CRYSTAL STRUCTURE

Nearly every substance known can, under certain conditions, be obtained in a crystalline state (Plate LX*b*), and crystals never fail to excite admiration and wonder by their colour, brilliancy or regularity of form. Such regularity is an outward and visible sign of an internal order and arrangement which has hitherto been concealed from us. Light passes through or is reflected from the plane faces, but just as the red rays pass through the dusty atmosphere while only the blue rays are scattered, so the whole of the waves of the visible spectrum are too coarse to be affected by the atoms and molecules of which a crystal is

composed. And we might have remained ignorant of these facts for all time if it had not occurred to Von Laue, in 1912, that as X-rays were, in effect, light waves of much shorter wavelength, they might be affected by atoms in the same way that dust particles scatter the shorter light waves from the sun. And surely enough when Friedrich and Knipping in 1913 passed a narrow beam of X-rays through a thin plate of crystal on to a photographic plate they secured a pattern which depended upon the form of the crystal they employed.

Plate LXI*a* is a photograph produced by the passage of the beam through zinc blende. The large spot in the centre is due to the portion of the beam which passed directly through the crystal, but the smaller spots all round it are produced by rays which were deflected by the atoms they encountered. The regular arrangement of these smaller

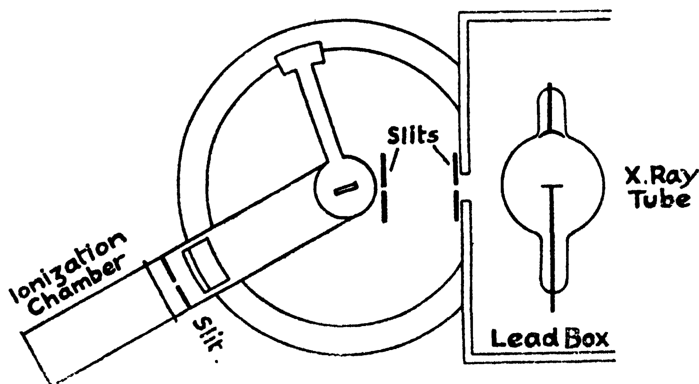


Figure 121. X-ray spectrometer

spots indicates a corresponding regularity of the atomic positions, but it is not possible to say from an inspection of the flat pattern exactly what this arrangement is. Nevertheless this regularity suggests analogy with diffraction by means of a grating rather than with the scattering of irregularly arranged particles in the atmosphere, and it occurred to W. H. Bragg to apply similar methods of investigation. So he devised the X-ray spectrometer for the purpose. In the hands of W. L. Bragg and other workers this instrument has made wonderful progress.

The X-ray spectrometer is an instrument in which an X-ray tube takes the place of a source of light, and a crystal takes the place of a prism or grating. The rays are directed upon a cleavage plane of a crystal at a certain angle, and are reflected from it. The reflected ray is received in an ionizing chamber. When it enters this chamber the air is ionized, and the fact is detected by means of an electroscope. The arrangement is shown diagrammatically in Fig. 121.

Now that the facts that crystal is bounded by plane faces suggests that the atoms or molecules are arranged in layers parallel to each cleavage plane, so that when the waves which constitute the X-rays fall upon each layer they will be partially reflected. The waves reflected from each layer (see Fig. 122), will reinforce or destroy one another according

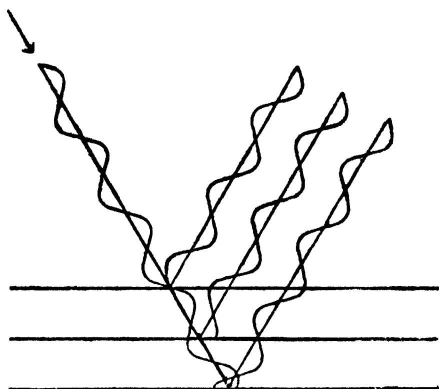


Figure 122. Diagram to explain interference in a crystal

to the even or odd number of half wavelengths they have travelled. This number will vary according to the angle at which the incident ray strikes the face, the distance apart of the two layers of molecules, and the wavelengths. If the wavelength is known then since the angle of incidence can be measured it is easy to calculate the distance between the

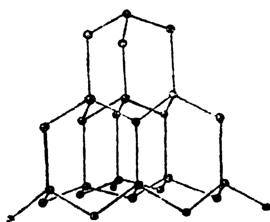


Figure 123. Crystal formation of diamond

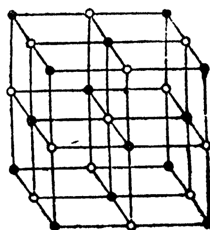


Figure 124. Crystal lattice of sodium chloride

atomic layers. Further, if the process be repeated for the other two faces it is possible to construct a model showing the arrangement of the atoms in space.

By such methods the lattices shown in Figs. 123 and 124 have been devised. Another method of building up crystal models is to use small

spheres in contact as in Plates LXI*b* (1, 2 and 3). In these examples it is not intended to convey the idea that the atoms are simple solid masses completely filling the spaces allotted to them. Each sphere represents merely a space which is not occupied wholly or partially by any other atom. Symmetrical as crystals are when viewed externally by ordinary light waves, the existence of law and order is much more strikingly manifested when they are analysed by the almost infinitesimal wavelets from an X-ray tube, and a beauty which is intelligible becomes more entrancing than it was before.

RADIOACTIVITY

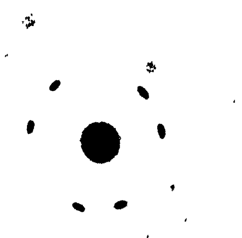
While bodies generally become luminous only when heated, there are a number of substances which can be induced to emit light without any rise of temperature. This light is usually of a characteristic colour. Thus, when a strong beam of sunlight is passed through sulphate of quinine in water a beautiful blue glow suffuses the liquid. Similarly, fluorescein gives a brilliant green glow; uranium glass, a canary yellow substance, appears green in strong light; and so on. This phenomenon is known as *fluorescence* and the glow ceases as soon as the light is cut off.

A number of other substances possess a similar property when excited by exposure to light, but retain it after the light has been removed. Thus Balmain's luminous paint after being exposed to strong light will continue to shine for some time in the dark. In order to distinguish this from the property described in the last paragraph, the term *phosphorescence* is used.

The glow on the walls of a vacuum tube when the dark space fills it is a case of fluorescence, and is apparently caused by the bombardment of the glass by the negative electrons. The Röntgen rays, again, are capable of producing brilliant affects, and the screen upon which the shadows are cast is usually coated with barium platinocyanide, a yellow salt which glows with a greenish light under the rays.

Shortly after the discovery of the X-rays by Röntgen, H. Becquerel repeated and extended some experiments made by Nièpce de St. Victor thirty years before, and demonstrated that the salts of uranium, which are capable of phosphorescence, will affect a photographic plate in the dark. He also showed that uranium caused the discharge of a gold-leaf electroscope. Further investigation revealed quite a number of substances possessing this property, and they were said to be *radioactive*, or to possess the property of *radioactivity*.

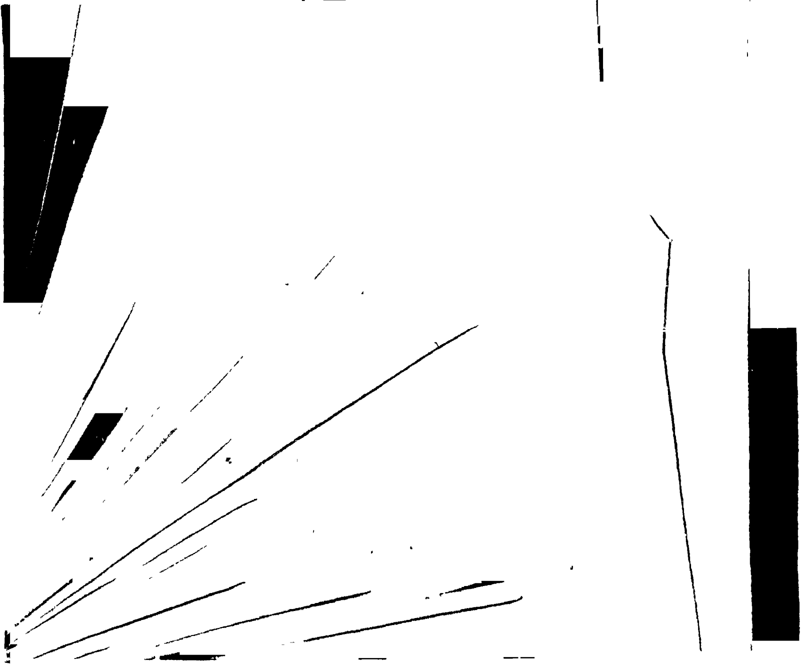
During the next four years, Pierre and Marie Curie examined a large number of minerals containing uranium, and found that their radioactivity varied considerably. They came to the conclusion that the cause was a substance or substances occurring in the minerals in minute but



LXI*a* X-radiogram of crystal of zinc blende, perpendicular to octohedron face



LXI*b*. Model showing arrangement of the atoms in crystals of (1) potassium or sodium chloride, (2) zinc sulphate, (3) aluminium oxide (ruby)

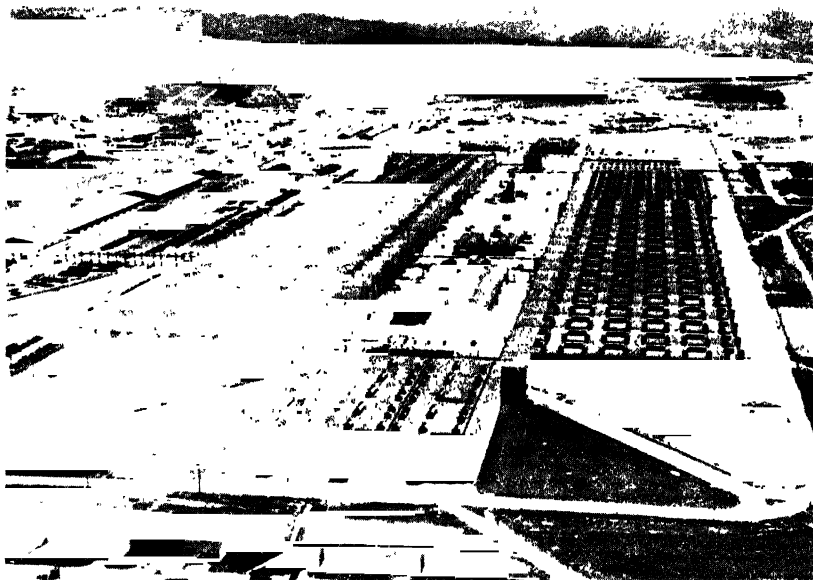


LXII*a*. Photograph showing trace of an α-particle in a

LXII*b*. Enlargement of a portion of LXII*a*



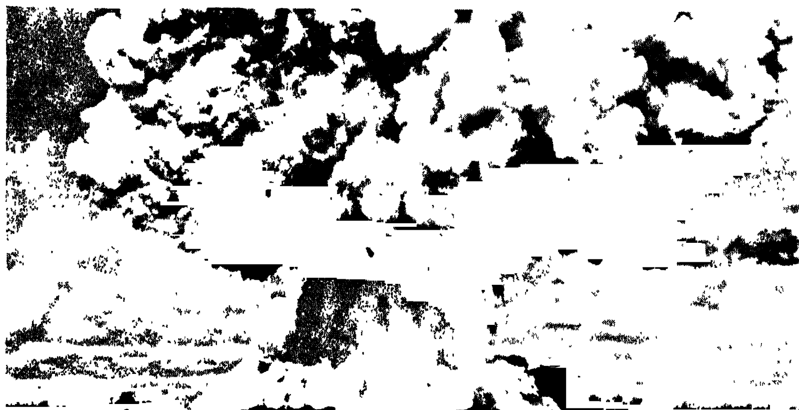
LXII*c*. Cloud-chamber photograph showing portion of a beam of X-rays



LXIII*a*. The diffusion plant at Oak Ridge, Tennessee



LXIII*b*. 'Bepo', the experimental pile at Harwell





LXIV*a*. Explosion of an Atomic fission bomb in the Monte-Bello Islands



LXIV*b*. Explosion of a Hydrogen bomb in the Marshall Islands

varying quantity. Finally by a long and tedious process, they extracted radium from pitchblende and found that it possessed a radioactivity over 1,000,000 times greater than the uranium salts which had previously been used.

One ton of pitchblende contains about 0·37 gramme, or less than $\frac{1}{70}$ of an ounce of radium, and only half of this can be obtained owing to losses in the process of extraction. In appearance and properties radium salts are very much like those of barium, and compounds of the two elements have to be separated by means of slight differences in solubility. When a solution of radium and barium bromides is cooled, the radium bromide separates out first, and this process has to be repeated over and over again until tests with the electroscope show no increase in activity. It is on account of the tediousness of this process that radium salts are worth many times their weight in gold.

The temperature of radium compounds is always about 1·5° C. higher than that of their surroundings. They decompose water, yielding oxygen and hydrogen, and this fact, together with other properties, indicates the liberation of an enormous amount of energy from an apparently inexhaustible store. Exact measurement shows that radium is continually producing sufficient heat to raise its own weight of water from the freezing-point to the boiling-point every hour.

THE CAUSE OF RADIOACTIVITY

It has been found that the radiation is of three kinds which are known as α (alpha), β (beta), and γ (gamma) rays. The α-rays are deflected slightly by powerful magnetic forces and have but slight penetrative power. A few layers of paper or an inch or two of air will cut them off entirely. The experimental evidence points to the view that they are atoms charged with positive electricity and shot off from radium with a velocity of nearly 20,000 miles a second.

The β-rays are strongly deflected in the opposite direction to the α-rays by much weaker magnetic forces. They carry a charge of negative electricity and have a velocity which, in some cases, approaches that of light —186,000 miles a second. In penetrative power and in practically every other respect except their greater velocity they are similar to the cathode rays in a Crookes' tube, and they are electrons with a negative charge.

The α-rays are not deflected by a magnet, and they penetrate many bodies which are opaque to ordinary light. They affect a photographic plate, excite fluorescence, and behave exactly in the same way as Röntgen rays; and like them their precise nature was, for some time, a matter of speculation.

The track of both α- and β-particles in air can actually be traced by a very beautiful method devised by C. T. R. Wilson in 1909. Many years

ago John Aitken found that if air or any other gas was saturated with water vapour, then cooling the gas did not cause separation of this moisture and the formation of cloud unless fine particles of dust were present. It was subsequently shown that as the diameter of a drop of water at any given temperature decreased, the tendency to evaporate increased. The rate of evaporation is clearly proportional to the area of the surface. Now the volume of a sphere of radius r is given by the formula

$$V = \frac{4}{3}\pi r^3,$$

and the area of surface by the formula

$$A = 4\pi r^2.$$

The volume of a sphere decreases, therefore, as the cube, and the surface as the square, of the radius. If the radius decreases from three to two the volume will decrease from twenty-seven to eight, while the area will decrease from nine to four, so that their ratio of area to volume will increase from nine twenty-sevenths to four-eighths, or from one-third to one-half. A small globule of water gradually decreasing in size will, when its radius reaches a certain lower limit, flash off into vapour. Conversely, the formation of drops from vapour is difficult unless there is some solid object, of more than this limiting curvature, upon which the drop can form.

Aitken showed that the fogs of towns were due largely to the smoke around the small particles of which the water could be deposited. The water-drops in fog or mist fall slowly to the ground. Their own weight pulls them down and the friction of the air on their surfaces offers resistance to their motion. The relation between volume and surface discussed in the preceding paragraph shows that the more minute the particles the greater will be the retarding influence of friction and the more slowly will they subside. Stokes showed how to calculate the rate of subsidence from the size of the drops and the viscosity of the air, so that if the rate could be measured the size of the drops could be calculated.

Now a charged atom or electron is capable of acting as a nucleus upon which moisture can condense. If air is charged with water vapour and, quite free from any radioactive or electrical influence, is caused to expand suddenly no mist is formed. But if it be exposed to a radioactive substance a cloud immediately forms on expansion, and by measuring the rate at which the upper surface of the cloud falls and knowing the amount of water precipitated from the extent of the expansion, the size and number of drops can be calculated.

The chamber in which the expansion was produced is shown diagrammatically in Fig. 125. When the space underneath the piston P was connected through the tube A with a larger vessel containing air at lower

pressure, the piston fell, the air in the chamber expanded, and a cloud was formed. The method enabled both α- and β-particles to be counted and a separation to be made. For if the volumes of the air before and after expansion was in the ratio 1 to 1·25, the α-particles alone were instrumental in producing cloud, while if the ratio was 1 to 1·31, the β-particles also became involved.

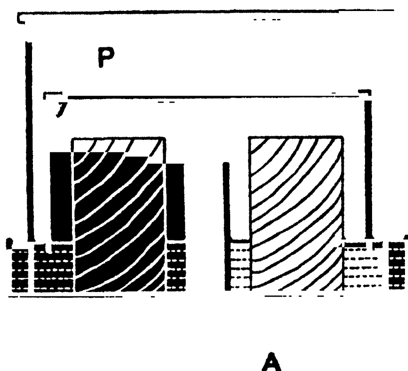


Figure 125. Diagram of Wilson's cloud chamber

Three years later, Wilson succeeded in rendering visible the track of a single α-particle. As the particle pursues its way through the gas it leaves a path of ions—either from itself or other atoms—and on expansion this is marked out by a streak of cloud which can be recorded on a photographic plate. Plates LXII*a* and *b* show the effect which is produced. Plate LXII*c* shows also the ions which are formed by a beam of X-rays traversing the gas. It has been found that a single α-particle produced from 2,000 to 6,000 ions per millimetre and a β-particle from twenty to thirty. The reason for the greater effect of the α-particles in rendering a gas through which they pass conductive is, therefore, explained.

The apparatus has been modified by Takeo Shimizu, who found that sudden expansion is not necessary to produce the cloud. In Fig. 126, K is the expansion chamber and the piston H is given a rapid oscillatory

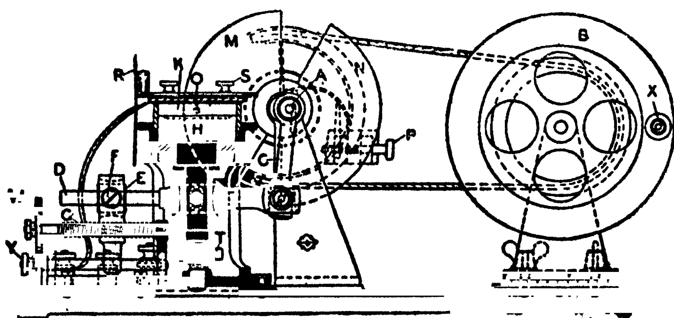


Figure 126. Section of Shimizu's apparatus for producing ions

motion by the crank X, operating through the rod D. The piston and the glass top of the chamber are covered with gelatin which will absorb a large quantity of water and keep the air saturated. From 50 to 200 expansions can be produced per minute.

It is necessary to distinguish between the properties of particles shot off from a radioactive substance with a velocity of 20,000 and 60,000 miles or more per second, and of those particles when their progress has been stopped by collision with the molecules of a gas under ordinary conditions of temperature and pressure. Their path is then zigzag, and though their velocity at any given instant is far greater than any we are able to obtain by mechanical means, the moving charges vary so rapidly in direction that the electrical and mechanical effects observed under low pressure are not possible.

THE NATURE OF RADIOACTIVITY

If a radium salt is dissolved in water and then evaporated to dryness, or if the dry salt is merely heated for a few hours, the activity is decreased. The emission of β- and γ-rays is stopped altogether for a time, and the quantity of α-rays is reduced to one-fourth. Yet apart from its radioactive properties the radium compound is in no way changed. It has the same appearance, and, so far as the balance is a test, the same weight as it had before. In course of time it recovers its activity, and this invariably occurs no matter how many times the operations may be repeated.

But some material substance escapes during the process. A gas—originally called *radium emanation*—can be collected, and this on examination is found to possess exactly the same amount of activity that the radium has lost. The quantity obtained is excessively minute.

The radioactivity of the emanation decays at the same rate as that at which the radioactivity of the original radium is recovered. After four days only half of the original activity remains, and within a month the emanation has disappeared from the tube and has been replaced by helium. This is a gas which for many years had been known to exist only in the sun, where it was recognized by a line in the spectrum corresponding with that of no terrestrial element. When Ramsay and Rayleigh discovered argon in the air, the former began an exhaustive search for this or other gases in the minerals of the earth's crust, and among the gases evolved on heating certain rare minerals he found helium.

The activity of the emanation as measured by the electroscope effect is due largely to the α-rays, which are now known to be electrons with a positive charge, and many times larger than the negatively charged electrons which constitute the β-rays. The fact that the rate of recovery

of radium is the same as the rate of decay of the emanation, suggests that the latter is formed by disintegration of the former. When the radium breaks down into emanation, α-particles are produced, and in the inter-atomic commotion that ensues the negative electrons are flung off, and the tremor which spreads outwards through space produces the effect of the γ-rays. The relatively greater activity of the emanation is explained by the statement that one-fourth of the α-rays are produced by the change of radium into the emanation, and three-fourths by the change of the emanation into helium, while the whole of the β- and γ-rays are formed in the second process. Both these changes are occurring in the original radium, and it is only when the accumulated emanation has been expelled that the separate influences can be distinguished.

Helium is not the sole product of the emanation. A minute trace of a radioactive solid is left behind which is called polonium and a whole series of substances are formed successively with an evolution of helium at each stage. Some of these exist for but a brief period, the successive changes occurring so rapidly that they can with difficulty be followed.

By a marvellously ingenious process, Rutherford succeeded in counting the number of particles emitted in a given time, and he detected the loss of a single member of the stream. By measuring the rate at which they are radiated he was able to calculate the average length of time which would be required for a radium atom to become extinct.

Now it has been shown that helium is a decomposition product of radium, and before radioactivity had been discovered Ramsay had found helium always present in minerals from which radioactive substances were subsequently obtained. It seemed probable, therefore, that radium itself was an intermediate product, formed by the disintegration at a slower rate of some other constituent of the minerals in which it is found. Moreover, as uranium and thorium—the naturally-occurring elements with the heaviest atoms known to chemists—are invariably present in these minerals, and possess a feeble radioactivity which suggests a slow rate of change, it seems feasible to imagine that there is a continuous process by which these elements are breaking down into others with lighter atoms of more or less stability. And this would go on until a stable substance was formed possessing no radioactive properties whatever.

It is important to note in this connection that the ratio of radium to uranium in minerals is very nearly constant—about 1 to 3,000,000—and this is what would be expected if uranium were the parent of radium. Moreover, if the average life of a radium atom is 25,000 years, the average life of uranium would be 3,000,000 times as long or 7,500,000,000 years.

It was concluded that uranium broke down into uranium X and helium, that uranium X broke down into a radioactive solid called

ionium, ionium was continuously and spontaneously passing into radium, that radium passed through its emanation (the inert gas niton) into polonium, and that finally polonium passed into lead.

ELECTRICITY AND MATTER

J. J. Thomson and his pupils, by experiment on the discharge of electricity through all gases, produced certain effects which are precisely similar to those which occur spontaneously during radioactivity. The β- and γ-rays have precisely the same properties respectively as the cathode stream and the Röntgen rays. So there is strong reason to believe that any view of the constitution of the radioactive substances is true of those which are not radioactive. At the same time the enormous amount of energy liberated during radioactive disintegration gave an idea of the magnitude of the forces which must exist in the interior of an atom.

The study of radioactivity, therefore, combined with that of electrical discharges in high vacua, leads to an electrical theory of matter in which the properties of each individual substance are determined merely by the number and arrangement of ultimate particles which are common to all the stuff of which the world is composed.

When α-particles are projected through a plate they are either bent out of their path or reduced in velocity, and by measuring the bending or the reduction in velocity it has been shown that the number of electrons in any atom is about half the atomic weight.

In these experiments it was noticed that a few of the α-particles were deflected widely and others were thrown right back. They had evidently come under the influence of heavier bodies and in some cases had actually collided with them. This led Rutherford to suggest that the whole mass of the atom resided in a nucleus of not more than $\frac{1}{1,000,000,000,000}$ cm. diameter, carrying a positive charge equal to half the atomic weight, and surrounded by a cloud of electrons which just neutralized the positive charge. This view has been confirmed by experiment, and the electrons are supposed to rotate round the nucleus like the planets round the sun.

Rutherford carried the transmutation of elements still further by bombarding them with α-rays. In this way he knocked hydrogen out of nitrogen, and proceeded to break up the complex atoms of other elements in the same way. Thus in 1921 he and Chadwick succeeded in obtaining hydrogen by the α-ray bombardment of sodium, boron, fluorine, aluminium, and phosphorus. There is now reason to believe that the old hypothesis of Prout, that all elements were built up out of an elementary particle, may be substantially correct, only in Prout's day the existence of electrons was not known.

But if the atoms of other elements have nuclei composed of such a particle they should all be whole numbers. In many cases this is not so, and the atomic weight elements which depart from this standard have been determined over and over again in order to discover, if possible, a source of error in the older experiments. But it has been all to no purpose. The atomic weight of chlorine remained at 35·45 and in the case of some elements the result of greater refinement and accuracy was to remove that atomic weight still farther from a multiple of unity. Experiments on radioactivity and the discharge of electricity in gases showed, however, that the properties of an element might be modified by the gain or loss of a β-particle which could not be detected by the most delicate balance, and J. J. Thomson showed how positive particles

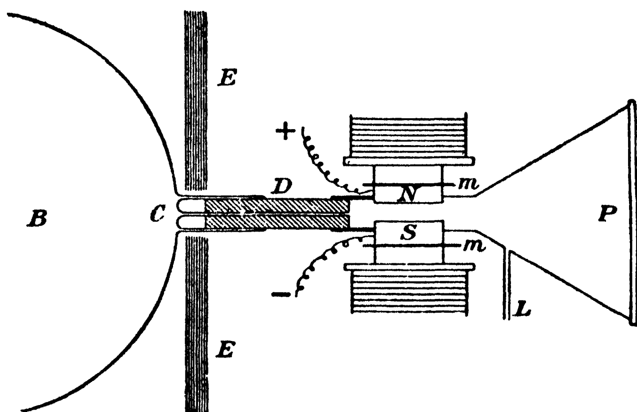


Figure 127. Sir J. J. Thomson's apparatus for studying the properties of α particles

differing in weight could be detected. In order to obtain positive particles he took advantage of the fact that when an electron is shot forward from the cathode of a Crookes' tube there is a sort of recoil, and a positive particle is shot backwards. If the cathode is perforated a stream of positive particles is produced behind it and moving in a direction opposite to the β-stream. Further, as these positive particles carry positive electrical charges, they can be deflected by the action of electric and magnetic forces in just the same way as the ordinary cathode stream.

The apparatus is shown in Fig. 127. The cathode is of aluminium with a fine copper tube from $\frac{1}{10}$ to $\frac{1}{100}$ of a millimetre in diameter running through it. Through this tube the positive particles pass into the vessel on the right, being exposed when necessary to the action of electric and magnetic forces on the way. At the end of this vessel is a photographic

plate. In the absence of electric and magnetic forces the particles strike the plate at a point exactly opposite the end of the fine tube. Under the influence of electric and magnetic forces they are bent and form a parabolic curve on the plate. The amount of bending depends on the mass, and as the positive particles from neon give two curves, he expressed the view that these were two kinds of neon atoms differing in atomic weight.

Many years ago it was suggested by Schützenberger and by Crookes that the atomic weights which had been determined might really be mean values, and that the atoms of any particular element might not be all of the same weight. The first indication that this might be true came from a study of the radioactive elements. Atoms possessing different atomic weights but similar in chemical properties, were called *isotopes* by Soddy. By the analysis of lead compounds from different radioactive minerals, Soddy, Richards, Hönigschmid and others proved that these isotopes exist.

F. W. Aston, working in J. J. Thomson's laboratory at Cambridge, very much improved the original apparatus and separated positive particles with an accuracy of one in a thousand. In this way he showed that if the atomic weight of oxygen is 16 that of hydrogen is 1·008, and that boron has isotopes weighing 10 and 11, neon 20 and 22, silicon 28 and 29, chlorine 35 and 37, argon 36 and 40, bromine 79 and 81, krypton 6, zenon 5, and mercury 6. With the exception of hydrogen all are whole numbers. Since theory shows that in close packing the effective mass may be decreased, and as hydrogen has been expelled from a number of the elements, it seemed probable that all atoms were built up from hydrogen nuclei.

Since isotopes do not differ from one another chemically they cannot be separated by chemical analysis.

The result of these investigations is the view that the electron is nature's unit of negative electricity and that the charge on the nucleus of a hydrogen atom is the corresponding unit of positive electricity. This has been given the name 'proton'. The unit positive charge was discovered in the form of the positive electron in 1932. In the same year, the neutron of unit mass and no charge was also discovered. The nuclei of atoms are now regarded as bundles of protons and neutrons.

The electrical theory of matter shed a new light also upon the mechanism of conductivity, for a current of electricity is merely the flow of electrically-charged particles or ions. If a current of electricity is passed through a gas, a movement of the ions takes place—positive in one direction, negative in the other. But except under very low pressures there are many collisions, freedom of motion is restricted, and recombinations occur. As the electromotive force is increased the resistance increases, until the electromotive force rises to such an extent that a

spark discharge takes place. This in itself produces ions, and explains the well-known fact that once an arc has formed the poles may be drawn apart to a distance across which the electricity would not previously flow.

In liquids and metals, again, the passage of the current can be increased indefinitely, because the positive and negative ions have fewer opportunities of recombining. The only limit is set by the heating effect.

While radioactive substances have the most powerful ionizing effect, hot bodies, X-rays and the minute waves of ultra-violet light, and probably chemical action have the same result. The influence of ultra-violet light waves has been used by W. H. Eccles to explain why the waves used in radio curve round the surface of the earth instead of spreading outwards into space. The upper layers of the atmosphere are relatively dry and invariably positively electrified. It has been suggested that the ultra-violet rays in sunlight, which are largely absorbed on their way to the earth's surface, separate the positive and negative ions, and that the latter are removed by acting as nuclei for the formation of water drops which appear as clouds and ultimately reach the earth as rain. The surface of the earth becomes negative, and the electric wave follows a path between that and the upper positive layer. This result could not have been foretold when Marconi actually transmitted wireless messages across the Atlantic.

Wonder at the experimental results is increased rather than diminished by a consideration of the magnitudes involved. The atom is about $\frac{1}{10,000,000}$ of a millimetre in diameter and a millimetre, we may remind the reader, is $\frac{10}{254}$ or roughly $\frac{1}{25}$ of an inch. The weight of an atom of hydrogen is $\frac{1}{1,000,000,000,000,000,000,000,000}$ of a gramme, and a gramme is $\frac{1}{28}$ of an ounce. The electron weighs about $\frac{1}{1,840}$ of the weight of an atom of hydrogen. But what the electron lacks in size and weight is made up in speed, for these infinitesimal particles travel with velocities that range from 10,000 to 60,000 miles a second.

ATOMIC ENERGY

When Pierre and Marie Curie measured the amount of heat continuously poured out by radium without any detectable loss of weight, they proved that the atom must contain extremely intense sources of energy. A more concrete picture of the process was revealed by the experiments by Rutherford, when he actually counted the atomic fragments flung out of exploding radioactive atoms. As he knew their mass and speed, he could calculate their individual energies exactly. The change of weight associated with the amount of energy released was far too small to be measurable by any existing balance.

In 1905 the process became clearer. Einstein's newly discovered

theory of relativity indicated that mass and energy were equivalent. When energy was released, it was accompanied by an exactly proportional diminution of mass. Matter was, in fact, congealed energy, so very intensely congealed that an ounce of matter, if annihilated, would produce enough energy to turn nearly one million tons of water into steam.

Einstein's formula, $E = mc^2$, in which m is the mass of the piece of matter under consideration, and c is the velocity of light, shows that the energy in matter is extremely large. The velocity of light is 186,000 miles a second, a very big number. c^2, the square of this, is enormous. So mc^2 must be enormous.

Even as early as 1905, then, physicists had a very precise idea of the intense amount of energy in matter. But the bulk of this energy seemed quite beyond human reach. The loss of mass which occurs when coal is burnt by ordinary chemical processes is extremely small, and the vast store of energy locked up in the coal as matter seemed quite beyond reach. Even in the very much more intense natural radioactive processes, the relative amounts of matter turned into energy were quite small, and most of the energy still seemed beyond reach. In the artificial disintegration of atoms accomplished by Rutherford in 1919, far more energy was wasted in securing the disintegration than was released as a result of it.

The first hopeful sign that atomic energy might be efficiently released was provided by the experiment of Cockcroft and Walton in 1932, in which they showed that atoms could be disintegrated by protons which had been artificially accelerated in an electric field. This showed that atoms could be disintegrated by man-made machinery. In their original experiment, Cockcroft and Walton disintegrated atoms of lithium by artificially accelerated protons. A relatively large amount of atomic energy was released in the disintegration of each lithium atom, but as many millions of accelerated protons missed for every one that hit the lithium atom, the energy balance-sheet for the whole experiment was on the debit side. But the fact that atomic energy could be released by machinery nevertheless strongly suggested that a more efficient form of machinery would soon be found. After the Cockcroft and Walton experiment, the practical release of atomic energy could not be far off.

Just before the Cockcroft and Walton experiment, another great atomic discovery was made. This was the discovery of the neutron by Chadwick. The neutron is a particle whose mass is almost equal to that of the proton, but has no electric charge. Owing to its lack of charge, as was foreseen by Rutherford, the neutron has an extraordinary capacity for penetrating atomic nuclei and disintegrating them. Within a short time of its discovery, Fermi showed that scores of different kinds of atoms could be disintegrated by neutrons, and even seemed to be able

to convert some of the heaviest atoms into new, hitherto unknown elements.

The bewildering flood of new data was investigated intensely by many physicists. Then, in 1938, Hahn and Strassmann showed that the atoms of the very heavy element uranium appeared not to be transmuted into still heavier atoms, but split into fragments of about one-half their size. They had discovered the famous phenomenon which Frisch named 'nuclear fission'.

When the uranium was split into two roughly equal parts, an immense amount of energy was liberated, about twenty times as much as in any hitherto known atomic process. This was because the sum of the masses of the atoms of the two elements into which the uranium atom split, e.g. barium and krypton, was substantially less than the mass of the uranium atom. The large amount of mass which disappeared reappeared as energy of movement in the flying barium and krypton atomic fragments

Joliot-Curie and others then made the capital discovery that when fission is induced in a uranium atom by a neutron, besides the two main fragments, e.g. barium and krypton atoms, several neutrons were also released. This suggested the possibility that each of these newly-released neutrons might disintegrate other uranium atoms, in turn releasing many more neutrons, and causing fissions to occur at an ever-increasing rate, and thus releasing atomic energy at an ever-increasing rate. This is known as a chain reaction. Such reactions are common in chemistry and occur, for example, in the spread of burning in an ordinary coal fire. As the amount of energy released in each uranium fission is millions of times more than in the chemical oxidation in the combustion of a carbon atom in coal, the chain reaction in a burning coal fire is very mild compared with that which may occur in a piece of uranium.

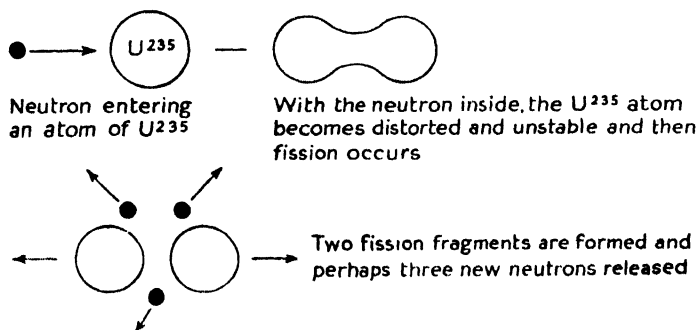


Figure 128. Scheme of chain reaction with U^{235}

It is evident that if each neutron which causes a fission leads to the production, on the average, of slightly more than one new fission-producing neutron, a chain reaction might be set up.

Chain reactions can vary in rate. If each uranium nucleus produced several neutrons, and each of these very quickly caused a fresh fission, the output of energy would grow very swiftly and be enormous. 1 lb. of uranium consumed by fission would produce as much energy as the burning of 1,000 tons of coal. If such a release occurred in a minute fraction of a second, it would have the form of an enormously violent explosion. But if it were arranged that the rate of fission remained approximately constant, and the output of energy kept up by continually feeding small amounts of uranium as fuel into the system (like coal into an ordinary fire), then a mild, steady release of atomic energy could be obtained.

The first line of development led to the atomic bomb. The second line of development, depending on a controlled chain reaction, leads to the steady release of atomic energy, which can be usefully applied for the manufacture of artificially radioactive substances, which can be used in medicine, chemical research, and many other new and valuable applications. Finally, the controlled chain reaction offers the prospect of a new major source of power, in addition to coal, oil, wood, and water.

The solution of these problems was complicated by the properties of natural uranium. This is not a simple substance. It consists of three constituents or isotopes U^{238}, U^{235} and U^{234}. The latter is present in very small quantity, and the proportion of U^{238} to U^{235} is as 139 to 1. The two chief isotopes, U^{238} and U^{235}, differ greatly in their reactions with neutrons. Neutrons easily build up a fast chain reaction in U^{235}. If a lump of this isotope is obtained in sufficient size, so that neutrons directed into it will remain inside for a sufficient time for the chain reaction to be built up, a terrific explosion is produced. If the lump is too small, an excessive percentage of neutrons escape from its surface, and lose the opportunity of participating in the reaction. The critical size is about that of a cricket ball.

But as U^{235} forms only 0·7 per cent of natural uranium, and its separation from the other isotopes is very difficult, the production of even a few pounds of pure U^{235} is extremely expensive.

The more plentiful isotope U^{238} has quite different but also even more valuable properties. When a slow neutron enters the U^{238} nucleus, it transforms the nucleus into U^{239}_{92}, a radioactive nucleus which spontaneously disintegrates and forms the nucleus of a new radioactive element of atomic number 93, which has been named neptunium, Np^{239}_{93}. Neptunium decays and forms yet another new element, of atomic number 94, Pu^{239}_{94}, named plutonium. Now the plutonium nucleus, as Bohr and Wheeler had forecast before it was discovered, resembles the

uranium nucleus in being subject to fission and chain reaction. Thus plutonium could be the material both for atomic explosives and atomic fuel for the controlled production of atomic energy. Further, as its parent U^{238} is 139 times as plentiful as U^{235}, plutonium is potentially far more plentiful than U^{235}, and very much less wasteful of natural uranium than restriction to the use of U^{235} would be.

However, it was decided to try to establish a successful chain reaction before exploring this attractive line. An arrangement was devised by which neutrons released in uranium fissions were prevented from causing fission in U^{238} nuclei and concentrated on U^{235} nuclei. After many experiments, lumps of uranium oxide and six tons of uranium metal were arranged in a lattice inside a mass of very pure carbon, the whole being piled up in an approximately spherical erection, and named a 'pile'. Fast neutrons arranged in the uranium bars escaped from their bars into the carbon, where they bumped against the carbon atoms until slowed down. As slow neutrons are specially apt to cause fission in U^{235}, the rate of fission might be increased when these slowed neutrons wandered back into the uranium bars. If the rate was raised sufficiently, a chain reaction might be established.

The pile was built in a racquets court in Chicago University. A chain reaction was successfully started in it on 2nd December 1942. The rate of release of atomic energy in it was at first very small, not enough to light a pocket flash lamp, but it was one of the great experiments of science, and showed that the controlled release of atomic energy was possible. Many scientists participated in this experiment, but the greatest contribution was made by E. Fermi.

A bigger uranium-carbon pile was then built at Oak Ridge, Tennessee, capable of releasing atomic power at the rate of about 1,000 h.p. The operation of this pile proved unexpectedly simple, and gave essential information for the steady production of plutonium.

One of the main problems is the extraction of the plutonium from the uranium, after it has been formed within it by neutron action. In order to carry this out, the pile is designed so that the uranium bars or slugs can, from time to time, be taken out of the lattice of carbon, and the plutonium removed from them by chemical extraction. The pile becomes a kind of carbon chamber for containing neutrons, in which pieces of uranium can be exposed until a quantity of plutonium is generated within them (Plate LXIII*b*).

Besides solving the difficult chemical problem of plutonium extraction, it was necessary to find out how to dispose of the enormous amount of energy which accompanied the production of plutonium at the rate of, say, 1 lb. per day. Much of this energy was released in the first place as exceedingly lethal radioactive radiations, and the whole process had to be conducted so that the health of the personnel was not

endangered. This was achieved by mechanizing the handling of all the material and observations by the methods of remote control. Another major problem was the finding of materials which would sufficiently withstand the intense corroding by the radioactive radiations inside the pile.

A pile which will produce 1 lb. of plutonium a day releases energy at the rate of about 500,000 kW., i.e. the output of a very big power station. In order to keep such a pile cool, a whole river of water must be used. The big piles erected at Hanford were cooled by a large diversion of water from the Columbia River.

As hot water attacks uranium, it was necessary to enclose the uranium bars in metal jackets which were good conductors of heat and relatively transparent to neutrons. They had to be gas-tight and retain the radioactive products released in the uranium. After many difficulties had been overcome, they were successfully made of aluminium.

A pile producing heat at the rate of 500,000 kW. emits its energy in the first place as radioactive radiations equivalent in intensity to those from a lump of radium weighing 500 tons. To prevent such radiation from hurting the operation, the pile must be surrounded by a wall of concrete many feet thick.

The intense radiations inside the pile provide an environment of a new type for structural materials. It was not known how ordinary materials would stand up to its corroding and destructive influence. For instance, under prolonged neutron bombardment, the heat conductivity, decline of resistance and elasticity of graphite are changed. It was found, however, that aluminium could be used for the cooling pipes and other parts. It was necessary to discover electrical insulators that would retain their insulating qualities for the construction of electrical instruments for recording what was happening inside the pile.

As there are always some stray neutrons about, a pile starts up spontaneously after its constituents have been appropriately arranged. When it has been running a sufficient time, uranium bars or slugs are removed for extraction of the plutonium and other radioactive products. This is done in a 'canyon', a row of concrete compartments, generally underground, in which there are a series of mechanized chemical laboratories. The uranium passes through these, and is treated, without any direct contact whatever with human operators. First it is dissolved, and then pumped through each mechanized laboratory, and put through chemical treatment, until in the last compartment of the 'canyon', a solution of a plutonium salt is obtained.

By taking the uranium slugs out in a systematic rotation, the plutonium can be removed from the pile at about the same rate as it is formed. In the Oak Ridge pile, uranium was removed at the rate of 300 kg. daily, and this contained about 1 gramme of plutonium and a

similar amount of other radioactive products. The chemical extraction is remarkably complete and successful.

Within six years of the discovery of fission, plutonium was being made at a rate of about ¼ lb. a day.

The preparation of quantities of the uranium isotope U^{235} can be done directly by electromagnetic separation. This utilizes the principles of the mass-spectrograph. If a beam of atomic particles of uniform velocity and the same nuclear electric charge, but differing mass, is directed into a magnetic field, the particles can be divided into several separate beams, according to the various masses. Thus a beam of natural uranium particles can be resolved into three beams consisting of the three isotopes, U^{234}, U^{235}, and U^{238}.

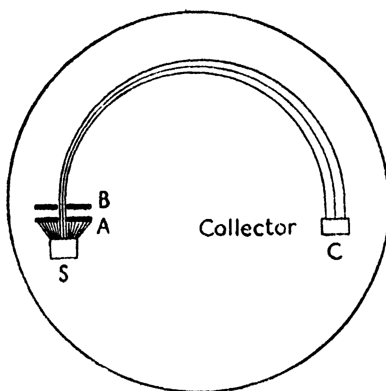


Figure 129. Scheme of an electromagnetic separator

The scheme of the electromagnetic separator shown in Fig. 129 consists of a magnetic field at right angles to the plane of the paper. The uranium particles, furnished as constituents of molecules in a vaporized uranium salt in the source S, are accelerated to a uniform velocity by an electric field between the two slits A and B. The magnetic field bends them round towards the collector C. It bends the molecules containing the light isotope U^{235} slightly more than those containing U^{238}. The collector is adjusted to catch the U^{235} beam, but not the U^{238}, or U^{234}.

The electromagnetic separation method produces relatively pure U^{235} directly. It was consequently very important in the production of the material for the first atomic bomb, which was required as quickly as possible.

A serious drawback of the method is due to the inefficiency of the beam. Only a small part of the uranium from the source gets into the

beam, and the remainder is deposited inside the apparatus, and has to be recovered by chemical treatment.

A more efficient but slower method of separation depends on diffusion. Light particles diffuse through porous membranes faster than heavier ones. Consequently, molecules containing U^{235} atoms diffuse slightly quicker than those containing U^{238}. The molecules used are those of uranium hexafluoride, which vaporizes at a moderate temperature. Unfortunately, it is very corrosive, and the relative masses are as 352 to 349, each molecule containing six atoms of fluorine besides one of either of the uranium isotopes. Owing to this very small difference in mass, the uranium hexafluoride vapour has to be diffused through a tremendous number of stages. Theoretically, about 1,700 are necessary in order to obtain 90 per cent U^{235}. In each stage the vapour is diffused through a porous membrane, the pressure on the entering side being about one atmosphere and on the receiving side one-tenth of an atmosphere. The gas is separated into two divisions, one enriched with U^{235} and the other stripped by a corresponding amount of U^{235}. It is arranged that this impoverished vapour has the same enrichment as the output from the stage below the one at which it was produced, so that it can be fed back into the system. The U^{235} is concentrated through a cascade of diffusion stages operated cyclically.

The technical problem of making membranes with sufficiently fine holes, which would not clog, and would stand up to the corrosive hexafluoride was very difficult. Thousands of pumps were required to send this corrosive vapour through miles of piping, all of which had to be resistant, free from leaks, and reliable. This presented new and great engineering problems (Plate LXIII*a*).

Two other serious problems are the huge volume of uranium hexafluoride in the plant, owing to the smallness of the enrichment at each diffusion stage. The plant itself is enormous.

THE ATOMIC BOMB

The liberation of energy in the fission of 1 lb. of uranium is about equal to that released in the explosion of 10,000 tons of T.N.T. If it can be liberated very quickly an enormous explosion can be produced. This could be done by arranging suitable conditions for a very fast neutron chain reaction to develop in a piece of U^{235} of appropriate size. The bomb should not be too big and unwieldy. Its core of U^{235} or plutonium should use as little as possible of these very rare materials. The bomb should be safe, and not liable to go off. It should be capable of precise control, so that it could be fired exactly at the desired moment.

As the development of the chain reaction will depend on fast neutrons, the core of atomic explosive must be large enough to give the fast neu-

trons a long enough track and time to be captured and cause fission and the release of more fast neutrons. If the core is too small, the fast neutrons will escape from its surface, and there will be no possibility of the chain reaction developing. Theory shows that the mass of the core should be between about 2 lb. and 200 lb. If it is surrounded with a neutron reflector, which deters the neutrons from escaping, it is somewhat smaller.

The fast neutrons have a speed of about 20,000 km. a second, and have to travel on the average about six thousand-millionths of a second before causing a fission. Within a millionth of a second something of the order of 100 successive generations of neutrons will have occurred, producing about a billion billion fissions, and enough energy to raise the temperature of the uranium to about ten thousand million degrees Centigrade, which is much higher than the temperature at the centre of the sun. The heat causes the central pressure to rise to about a million million times that of the atmosphere, or about 14,000,000,000,000 lb. per sq. in.

This intense explosive rise of pressure disperses the material of the bomb at enormous speed, and if the diameter of the core is greater than a certain maximum size, its outer material is blown away before the chain reaction has had time to develop in it. The atomic explosion, once it starts, catches up and overtakes the chain reaction. Owing to the explosive dispersion, perhaps only about 2 per cent of the uranium in the core actually undergoes fission, and the rest is blown away as waste.

Slight scientific improvements in the design of the bomb may lead to big increases in explosive power, and it may be very much more profitable to spend a relatively small sum on scientific brains than a very large sum in making large quantities of expensive material for less efficient bombs.

A piece of fissionable material which is below the critical size is perfectly safe. A bomb can be made by assembling two or more pieces, so that they make one lump bigger than the critical size. The pieces would have to be put together so quickly that the chain reaction would not develop too far before all of the pieces were in contact, otherwise a premature explosion might occur, and most of the fissionable material be dispersed before the maximum possible amount of it had been consumed. An obvious way of bringing the pieces of fissionable material together very quickly would be to blow them together with an ordinary high explosive.

The first atomic bomb was exploded in New Mexico on 16th July 1945. It made its huge plume 40,000 ft. high, after a flash more brilliant than the sun. All who saw the phenomenon watched it with awe. It had been accomplished necessarily without any intermediate trials, for the bomb could not be smaller than a certain size. Every item of the design

depended in the end entirely on theoretical calculations. If the bomb was to succeed they had all to be correct. Yet within six years from the discovery of fission every theoretical, every experimental problem was successfully solved (Plate LXIV*a*).

The 'fission' bomb has been followed by the 'fusion' or 'hydrogen' bomb, in which atoms of hydrogen combine to form helium, with enormous output of energy. Unlike the 'fission' bomb, the 'hydrogen' bomb is theoretically unlimited in size, and therefore presents a serious threat to the ultimate survival of life on earth (Plate LXIV*b*).

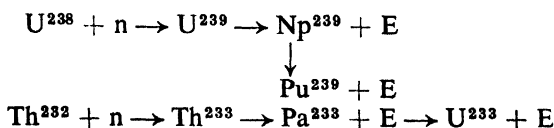
ATOMIC POWER

The use of atomic power for industrial purposes has already begun on a small scale, and will certainly develop. An atomic power-station which regularly produces 5,000 kW. started running in the Soviet Union in 1954. At the present stage of technical knowledge there are, however, many very serious technical problems that have not yet been solved.

The energy required to drive an ordinary motor-car through its life is about equal to that released by the fission of about a third of an ounce of uranium. This would seem to be extremely convenient—the car could, as it were, be driven throughout its life by a small coin of fissionable material put in at the beginning. Such a convenient concentration of power would appear to be even more suited to aircraft propulsion. But these prospects are immediately controlled by the consideration that very much more fissionable material would in fact have to be carried, and the pile utilizing it would be emitting very intense and dangerous radiations. To be safe, the atomic power unit would have to be encased in concrete at least six feet thick and weighing fifty tons.

Such a weight would prevent an atomic pile from being used as a motor-car power plant, but it would not be at all impossible in a locomotive or a ship, or even in a big aircraft. Statements have already been published indicating that atomic power plants have been used for driving submarines.

The use of atomic energy for driving big electrical generating plants seems the most immediately promising. The consumption of six tons of U^{235} annually would give sufficient energy to equal the whole of the present annual output of the electrical supply system of Britain. At present, consideration is being given to piles of the breeding type. These develop energy by burning a primary nuclear fuel such as U^{235}, but produce at the same time a greater amount of secondary nuclear fuel than they consume primary fuel. This is done by surrounding the primary core with uranium or thorium. Surplus neutrons from the core cause the following reactions



$$U^{238} + n \rightarrow U^{239} \rightarrow Np^{239} + E$$
$$\downarrow$$
$$Pu^{239} + E$$
$$Th^{232} + n \rightarrow Th^{233} \rightarrow Pa^{233} + E \rightarrow U^{233} + E$$

The thorium system is preferable because the chemical separation of U^{233} from thorium is easier, and plutonium is more dangerous to health.

A pile of the breeding type working on U^{235} as primary fuel could convert natural uranium into plutonium, which would act as secondary fuel. The pile would continue to burn until the radioactive products poisoned the reaction. A pile containing 200 tons of uranium metal might run from ten to thirty years and consume 1 per cent of its uranium before its chain reaction ceased.

A consumption of about 600 tons of uranium metal would be sufficient to supply the annual power needs of Britain. Such a consumption of uranium would be possible only if low-grade ores could be extracted at reasonable cost. At present, it appears that nuclear power costs will be of the same general order as conventional power costs.

In 1950 Cockcroft forecast that the first experimental power reactors will be built during the next three to five years. During the next five years, operational experience will be gained, and the first full-scale nuclear power plant will be designed. In the same period, the solution of the accompanying chemical, engineering and metallurgical problems will be sought.

The British Electricity Authority operates its boilers at 455° C. Already, at Harwell, improvements in metallurgy have led to the raising of the working temperature to 300° C. Research is proceeding on the use of beryllium and zirconium, which promise to be usable at the higher temperature. The development of jet engines running at high temperatures and using nuclear power still seems far off.

The first atomic central heating plant was opened at Harwell in 1951. Eighty offices draw their heat from BEPO, the large experimental pile. The installation saves 1,000 tons of coal annually.

The constant hot water is obtained by placing a heat exchanger in the outlet air duct of the pile's air-cooling system. The water is heated to 130° F. The heat output for the first instalment of the system was about equal to that of two hundred electric fires.

Such are some of the present developments, but any large-scale development of nuclear power is unlikely before at least the following decade.

The numerous radioactive materials produced in piles already have a very wide and rapidly expanding field of application.

Strontium 90 is used in thickness gauges, by measuring the amount of radiation it sends through strip paper, plastic, cardboard, and steel.

Thallium 204 is being used as a 'static eliminator' for dissipating unwanted electric charges.

Radioactive sodium is used for detecting leaks of water from a lake containing fifty million gallons into coal-pits beneath. Radioactive bromine is used to check the ventilation system of factories. Radioactive sodium has been used to check the effectiveness of putting one grain of vitamin in five tons of cattle food. Radioactive cobalt has been used in pipe-line operations. Blockages are located by mixing radioactive materials in the cleansing fluid.

Isotopes have been used with great effect in the study of the synthesis of hydrocarbons and on the rate of polymerization catalysts. In pure chemistry, the application of radioactive isotopes has brought an immense advance in the range and delicacy of chemical analysis.

The future of atomic energy is still rather obscure, in spite of the very remarkable discoveries that have been made. We can be fairly sure, however, that many further discoveries will be made as astonishing as those which have already been achieved. We know we have been launched into a new age, even if we cannot as yet see its outlines clearly.

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